MAR 25 '55 A

Index in dec. issue of V. 25 + 26
V. 25 (1955) V. 26 (1956)

Volume 25 MARCH, 1955 Number 1

V. 27 #1
Jan. 57

Journal of Sedimentary Petrology

10374

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Petrographic comparison of some loess samples from Western Europe with Kansas loess ..... *Ada Swineford and John C. Frye* 3

Marine sediments north of Scripps Submarine Canyon, La Jolla, California ..... *C. Stanley Wimberley* 24

Two unusual occurrences of microstylolites ..... *Benjamin H. Burma and Charles M. Riley* 38

Sand pipe from the sea floor off California ..... *Hiroshi Niino* 41

Classification of Permian rocks of Western Texas by a versenate method of chemical analysis ..... *Richard G. Guerrero and Charles T. Kenner* 45

Transportation of rocks by driftwood ..... *K. O. Emery* 51

A spot test for dolomitic limestones ..... *Virgil I. Mann* 58

Origin of stylolites: a discussion ..... *B. M. Shaub* 60

Clastic casts of halite crystal imprints from the Rome formation (Cambrian) of Tennessee ..... *H. K. Brooks* 67

An occurrence of gypsum in Southwest Texas ..... *P. H. Masson* 72

DISCUSSION

Some remarks on cyclic calcareous sedimentation as an index of climatic variations ..... *Albert Carozzi* 78

Journal of Sedimentary Petrology

J. L. HOUGH, EDITOR
University of Illinois
Urbana, Illinois

RALPH E. GRIM, ACTING EDITOR
University of Illinois
Urbana, Illinois

ASSOCIATE EDITORS

W. C. KRUMBEIN
Northwestern University
Evanston, Illinois

K. O. EMERY
University of Southern California
Los Angeles, California

R. DANA RUSSELL
Ohio Oil Company
Findlay, Ohio

The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in March, June, September and December.

The subscription price of the *Journal of Sedimentary Petrology* is $5.00 per year prepaid to addresses in the United States.

Single numbers, $2.00 each ($1.50 to members).

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $5.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about *Journal* subscriptions, rates, memberships, change of address, and non-receipt of preceding number should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts and purely editorial matters should be addressed to The Editor, *Journal of Sedimentary Petrology*, University of Illinois, Urbana, Illinois.

Annual Membership dues, including the Journal of Paleontology .....$ 8.00
Annual Membership dues, including the Journal of Sedimentary Petrology .. 5.00
Annual Membership dues, including both Journals 13.00

Non-Member Subscriptions to Journal of Paleontology $15.00; Outside U.S. $15.40
Non-Member Subscriptions to Journal of Sedimentary Petrology
$6.00; Outside U.S. $6.40

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN

PRINTED IN THE U.S.A.

Journal
of
Sedimentary Petrology

VOLUME 25
MARCH, 1955-DECEMBER, 1955
Nos. 1-4

J. L. HOUGH, EDITOR
R. E. GRIM, ACTING EDITOR

PUBLISHED BY THE
SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
A DIVISION OF
THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
Box 979, Tulsa, Oklahoma

Volume 25 MARCH, 1955 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

CONTENTS

Petrographic comparison of some loess samples from Western Europe with Kansas loess ..... *Ada Swineford and John C. Frye* 3

Marine sediments north of Scripps Submarine Canyon, La Jolla, California ..... *C. Stanley Wimberley* 24

Two unusual occurrences of microstylolites ..... *Benjamin H. Burma and Charles M. Riley* 38

Sand pipe from the sea floor off California ..... *Hiroshi Niino* 41

Classification of Permian rocks of Western Texas by a versenate method of chemical analysis .... *Richard G. Guerrero and Charles T. Kenner* 45

Transportation of rocks by driftwood ..... *K. O. Emery* 51

A spot test for dolomitic limestones ..... *Virgil I. Mann* 58

Origin of stylolites: a discussion ..... *B. M. Shaub* 60

Clastic casts of halite crystal imprints from the Rome formation (Cambrian) of Tennessee ..... *H. K. Brooks* 67

An occurrence of gypsum in Southwest Texas ..... *P. H. Masson* 72

DISCUSSION

Some remarks on cyclic calcareous sedimentation as an index of climatic variations ..... *Albert Carozzi* 78

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

The nature of corrosion zones in the Middle Ordovician of Minnesota. By N. Prokopovich.

Composite end members in facies mapping. By W. C. Krumbein.

Mineralogical-particle size variations in oriented clay aggregates. By L. G. Schultz.

Diagnostic heavy minerals in the regolith of Massachusetts. By M. A. Light.

Origin of the Salina Salt of Michigan. By L. F. Dellwig.

Sandstone classification: relation to composition and texture. By J. Bockman.

Clay minerals of the Neuse River Estuary. By G. M. Griffin and R. L. Ingram.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 3–23
PLS. 1–3, FIGS. 1–3, MARCH, 1955

PETROGRAPHIC COMPARISON OF SOME LOESS SAMPLES FROM WESTERN EUROPE WITH KANSAS LOESS

ADA SWINEFORD AND JOHN C. FRYE[1]
State Geological Survey, University of Kansas

ABSTRACT

Fifteen samples of loess collected in 1952 in Italy, France, Germany, and Belgium were studied by mechanical and chemical analysis, X-ray diffraction, and light and electron microscopy. These data are compared and contrasted with similar data from 47 samples from Kansas and Nebraska. It is shown that in spite of the similarities of the loess of the two regions in field appearance, relationship, buried soil profiles, texture, and stratigraphy, the mineralogy of the European samples contrasts strongly with that of the Kansas samples. Abundant montmorillonite and volcanic ash shards in the Kansas samples are the most striking points of difference, but strong variations are also noted in other minerals of the coarse fraction as well as in other of the clay minerals.

INTRODUCTION

Loess, or massive well-sorted silt with some clay and very fine sand, is perhaps the most widespread of surficial deposits in the northern hemisphere. Although there is lack of general agreement concerning its origin—it is probable that deposits included by various workers under the name "loess" represent deposits of several origins—western Europe, and particularly the Rhine Valley, has long been a classic region for study of these massive silts. The central Great Plains of the United States (Kansas and Nebraska) contain more widespread and thicker deposits of surficial silts that bear a striking superficial similarity to the European deposits. We have had opportunity during the past decade to study in some detail the loess deposits of the central Great Plains (Swineford and Frye, 1951; Frye and Leonard, 1951); it is our purpose here to present petrographic data on samples from western Europe and to compare and contrast their properties with typical loess from Kansas and Nebraska.

Opportunity to examine loess deposits and to collect samples in western Europe was made possible to Frye during the summer of 1952 by a grant from the University of Kansas Endowment Associa-

FIG. 1.—Map of a part of western Europe showing location of loess samples described.

[1] Present address: Illinois State Geological Survey, Urbana, Illinois.

tion and the generosity of Prof. Raymond C. Moore of the University of Kansas with whom he traveled. Data on 15 samples from 10 localities in Italy, France, Germany, and Belgium are reported here (fig. 1); data on 47 samples from 42 localities in Kansas and Nebraska have previously been published (Swineford and Frye, 1951). Field guidance in the case of all but one of the localities described here was in company of local authorities; the single exception was found by following maps and notes furnished by them. Ages were assigned, and collateral data in many cases were furnished by them, and their assistance is hereby acknowledged. In the Rhine Valley in the vicinity of Wiesbaden, Germany, we were guided by Prof. Dr. Franz Michels and Dr. Ernst Schonhals, Hessisches Landesant für Bodenforschung, Wiesbaden; at Mauer, Germany, by Dr. Arthur Rosler, Geologische-Paläontologische Institut, Heidelberg; in the vicinity of Strasbourg, France, by Prof. Dr. Georges Dubois and Dr. Paul Wernert, Laboratoire de Géologie, Université de Strasbourg; in the vicinity of Torino, Italy, by Prof. C. Socin, Istituto di Geologia, Torino; and in the vincity of Landen, west of Liége, Belgium, by Prof. F. Gullentops, Laboratoire de Géologie, Université de Louvain. Prof. F. Schaub, Naturhistorisches Museum, Basel, Switzerland, furnished maps and notes for the location of exposures in the vicinity of St. Vallier, France, along the Rhone Valley.

General Stratigraphy

Loess deposits of the northern hemisphere are predominantly of late Pleistocene age. In the Great Plains region loess deposits are Illinoian and Wisconsinan in age and are subdivided by the use of buried soils and molluscan faunas into three stratigraphic units: the Loveland, Peoria, and Bignell silt members of the Sanborn formation (Frye and Leonard, 1951; 1952). Of these three the Peoria is by far the thickest and most extensive; all samples used for comparison are from this early Wisconsinan unit.

Stratigraphic placement of the samples from western Europe is with respect to the standard section of the Alpine region. Most of the European loess samples described here are assignable to the Würm; however, sample 10 from the Rhine Valley is of a Chernozem soil developed in loess tentatively assigned to the Riss; sample 6 from Achenheim is assigned to the late Mindel or Riss; and samples 3 and 4 along the Rhone Valley are dated only by their position above a deep, mature soil developed in the top of deposits that have yielded diagnostic Villafranchian vertebrate fossils.

In general loess samples studied from both North America and Europe are of corresponding age, and are assigned to the last major episode of continental glaciation.

Laboratory Procedure

Mechanical analyses of the 15 samples were made by the same method used for the Kansas samples in 1950 (Swineford and Frye, 1951) in order to facilitate comparison. The results are shown in table 1, and a few cumulative size-frequency curves are plotted in figure 2.

Chemical analyses of the 15 European samples were made under the direction of Russell T. Runnels in the laboratories of the State Geological Survey of Kansas, and are shown in table 2, along with calcium carbonate content computed by Runnels.

The size fraction between 44 and two microns (in all samples except those from Torino) consists predominately of clay-coated quartz grains, plus calcite and feldspars in those samples which also contain calcite and feldspars in the coarser fractions. Micas and rock fragments are less abundant than in the fractions coarser than 44 microns. Most of the heavy minerals are within the 20–44 micron fraction.

The silt and sand fractions coarser than about 20 microns were examined with binocular and petrographic microscopes. Detailed observations were restricted to

TABLE 1.—*Mechanical analyses of samples of loess from western Europe and selected samples from Kansas and Nebraska*

No.	Location	Size distribution in phi units (percent by weight)													M_ϕ	σ_ϕ	Md_ϕ	QD_ϕ	Sk_ϕ	PD_ϕ
		−2– −1	−1–0	0–1	1–2	2–3	3–4	4–4.5	4.5–5	5–6	6–7	7–8	8–9	9–10	10+					
1	Italy				0.1	1.0	24.8	27.1	19.5	15.8	4.9	2.3	1.6	1.1	1.9	4.79	1.411	4.45	0.56	0.723	1.35
2	Italy			0.0	0.1	1.2	14.1	18.5	19.0	18.3	8.7	4.3	3.0	3.3	4.7	5.55	1.892	4.90	1.06	1.031	2.35
3	France			0.0	0.0	0.4	10.7	21.6	25.7	21.1	9.5	4.7	3.0	2.2	3.5	5.32	1.633	4.85	0.68	0.863	1.82
4	France		0.1	0.1	0.4	1.1	6.7	22.6	18.3	26.7	16.5	8.1	4.7	3.1	3.1	6.33	2.298	5.50	1.72	1.084	3.20++
5	France			0.0	0.1	0.2	0.6	7.5	21.7	34.1	11.8	4.8	3.7	3.1	9.7	6.03	1.982	5.45	0.85	0.878	2.73
6	France			0.0	1.0	0.7	1.1	10.8	20.1	32.2	11.9	5.1	4.1	3.4	9.6	6.08	1.959	5.45	0.92	0.965	2.75
7	Germany			0.2	0.4	0.5	2.2	10.4	19.3	31.7	14.1	6.8	5.0	3.7	5.9	6.00	1.785	5.50	0.91	0.840	2.27
8	Germany			0.1	0.3	0.5	3.4	12.1	21.2	27.5	10.5	4.9	3.2	2.7	9.4	5.76	2.175	5.00	0.94	1.048	2.83
9	Germany	0.1	0.7	0.7	2.4	1.1	4.3	9.5	16.1	21.6	10.7	6.2	4.9	4.3	18.2	6.46	2.482	5.70	1.88	0.919	3.43++
10	Germany		0.2	0.6	1.2	2.3	4.3	9.5	16.1	21.6	10.7	6.2	4.9	4.3	18.2	6.46	2.482	5.70	1.88	0.919	3.43++
11	Germany	1.1	2.3	1.4	1.4	1.4	1.6	9.5	19.8	29.6	9.8	4.0	3.1	2.4	12.7	5.80	2.536	5.30	0.94	0.591	3.33++
12	Germany	0.0	0.2	0.4	1.7	3.8	8.2	14.2	20.7	25.7	8.0	3.0	2.3	2.8	8.9	5.54	2.131	5.03	0.82	0.718	2.92
13	Germany		0.2	0.8	2.1	5.7	9.2	14.8	18.2	23.5	8.3	3.7	2.0	1.9	9.7	5.46	2.226	4.95	0.89	0.674	3.15
14	Germany		0.1	0.3	0.9	2.5	6.1	11.6	17.2	28.5	10.6	4.6	2.8	2.2	12.7	5.96	2.206	5.35	1.02	0.830	3.88+
15	Belgium				0.0	0.9	12.4	33.7	34.5	6.5	2.2	1.9	5.1			5.54	1.568	5.05	0.52	0.938	1.58
	Nebraska[1]					1.8	18.9	32.2	22.6	16.4	4.2	1.5	0.6	0.4	1.3	4.69	1.164	4.45	0.46	0.619	1.16
	Kansas[1]					1.6	3.1	28.9	28.0	23.2	7.2	2.8	1.7	1.7	1.7	5.15	1.323	4.79	0.56	0.816	1.28
	Kansas[1]						0.4	11.9	21.4	38.3	14.8	5.8	3.1	1.6	2.7	5.72	1.376	5.43	0.68	0.632	1.52
	Kansas[1]					0.1	7.5	31.8	30.7	19.7	4.3	2.0	0.6	1.4	1.8	4.97	1.226	4.67	0.43	0.734	1.00
	Kansas[1]						0.6	17.6	36.2	34.1	5.6	2.1	0.5	1.2	2.1	5.22	1.176	4.94	0.44	0.663	0.92
	Kansas[1]				2.2	21.4	19.5	11.8	13.0	17.6	7.6	3.2	1.2	0.8	1.8	4.43	1.747	4.29	1.13	0.240	2.04

[1] Swineford and Frye, 1951.

grains coarser than about 44 microns, because their mineralogy could be more readily identified.

X-ray diffraction patterns were made from <2 micron samples oriented on glass slides. Patterns were made in each case from the untreated clay and from acid-treated (cold 0.1 N HCl) clay. Selected patterns were also made from glycerol-wet preparations and from clay which had been heated to 550°–600° C. for 30 minutes. Diffractometer patterns were made with a GE XRD3 unit operated at a scanning speed of 0.2° 2θ per minute and using nickel-filtered copper radiation. Scanning was begun at 2° 2θ for several samples, but no low-angle superlattice reflections were observed. The observed *d*-values and estimated intensities are shown in tables 3, 4, 5, and 6. Some of the diffractometer patterns are shown in figure 3.

The <2 micron fraction characteristically consists of a complex mixture of layer silicates, calcite, and quartz. All samples contain significant quantities of illite and/or comminuted muscovite (and other micas) and most have smaller amounts of kaolinite. The most obvious differences among the loesses lie in the relative proportions of these minerals and in the presence or absence of a 14.7 Å mineral and of a mineral which expands on treatment with glycerol. As will be noted in descriptions of individual samples, some of these minerals have mixed-layer characteristics. The mineralogy of the loesses is so complex, however, that definitive interpretations would have doubtful validity.

In general, the observable effect of treatment with cold 0.1 HCl is as follows. If montmorillonite is present it is converted to hydrogen clay and a broad 13 Å reflection is produced. The 14.7 Å reflection may tend to be sharpened (by shifting of 15 Å band, in part?) and in most instances shifts

TABLE 2.—*Chemical analyses of samples of loess from western Europe and selected samples from Kansas*[1]

No.	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	K_2O	Na_2O	S	Loss 1000° C.	$CaCO_3$, calc.	Total
1	47.43	9.80	4.91	1.42	16.10	3.11	0.13	tr	1.43	0.89	tr	14.59	28.61	99.81
2	64.63	16.03	6.56	0.82	1.72	2.61	0.19	tr	2.19	1.10	nil	4.44	2.62	100.29
3	53.55	8.51	3.24	0.79	16.64	0.51	0.11	tr	1.17	0.57	tr	14.72	29.46	99.81
4	66.92	12.71	4.34	0.90	4.36	0.77	0.13	tr	1.76	1.02	tr	6.28	7.48	99.19
5	58.84	11.74	4.67	0.91	7.99	2.55	0.15	nil	1.70	0.84	0.02	9.87	13.89	99.26
6	43.57	5.78	2.68	1.28	22.87	2.44	0.13	tr	1.08	0.90	tr	19.89	40.69	100.62
7	63.44	8.75	3.64	1.36	8.83	1.71	0.11	nil	1.54	1.17	tr	9.17	15.65	99.72
8	80.62	9.03	2.88	1.18	0.53	0.64	0.07	tr	1.43	1.08	tr	2.34	0.77	99.80
9	54.05	8.17	2.83	1.07	14.60	2.09	0.11	tr	1.41	1.04	nil	14.12	25.81	99.49
10	70.62	10.41	4.19	0.45	3.98	1.16	0.05	nil	1.83	0.89	nil	5.50	6.98	99.08
11	58.88	8.37	3.13	0.73	11.88	2.19	0.11	tr	1.44	0.84	0.02	11.91	20.95	99.48
12	59.36	6.13	2.66	1.89	12.79	1.90	0.10	tr	1.45	1.03	tr	12.31	22.76	99.62
13	59.04	7.44	2.67	1.13	12.96	1.55	0.09	tr	1.45	1.00	nil	12.50	22.92	99.83
14	51.86	6.82	2.40	0.89	17.59	1.69	0.08	tr	1.21	0.92	nil	16.78	31.20	100.24
15	72.77	7.09	2.98	1.79	5.33	1.02	0.10	tr	1.64	1.04	tr	5.76	9.94	99.52
[2]	73.33	12.00[4]	3.02	—	2.67	1.06	0.08	tr	2.55	1.48[5]	—	3.89		
[3]	72.35	13.56[4]	3.46	—	2.04	1.77	0.14	tr	2.78	0.24[5]	—	3.66		

[1] Analyses by Russell Runnels, State Geological Survey of Kansas.
[2] Doniphan County, Kansas (Frye and others, 1949, p. 85).
[3] Norton County, Kansas (Frye and others, 1949, p. 85).
[4] Includes TiO_2.
[5] Determined by difference.

to about 14.5–14.3 Å. Acid treatment also tends to sharpen and accentuate the 4.75 and 3.55 Å reflections in clays which give a strong 14.5 Å reflection. Orientation is improved and basal reflections are enhanced in acid-treated samples by removal of nonflaky calcite particles. Acid treatment also produces a broad unexplained 8 Å band in several samples.

Glycerol saturation produces a weak to moderate 18 Å reflection in some of the clays. This reflection is not as symmetrical as that in bentonites or in Kansas loess, but seems to tail off in the low-angle

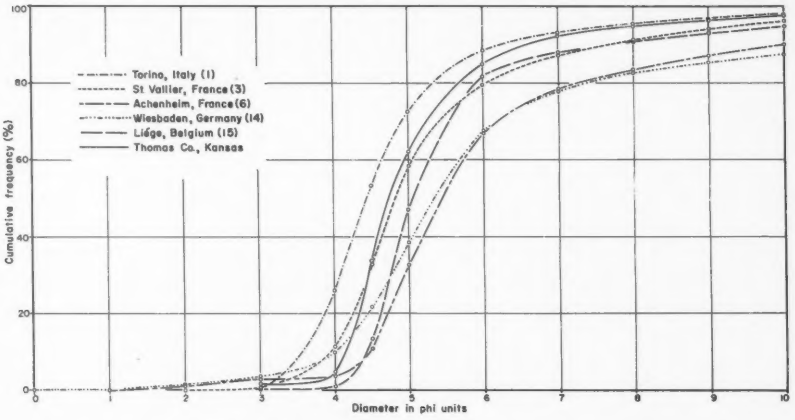


FIG. 2.—Selected cumulative size frequency distribution curves for samples from western Europe (samples 1, 3, 6, 14, and 15) compared with the curve of a typical sample from northwestern Kansas (Swineford and Frye, 1951).

direction. Glycerol improves the symmetry of the 10 Å peak in some samples.

Heat treatment for 30 minutes at 550°–600° C. shifts the 14.7 Å reflection in most of the clays to 14.2–14.0 Å and tends to sharpen it. The 7 Å reflection is destroyed in most clays but not in all of them. All kaolinite reflections are destroyed. Most of the clays show a broad weak reflection at 11.2 to 12.3 Å (accompanied by a reduction in intensity of the 14 Å peak) after heating. The observed *d*-values for heated clays are shown in table 6. Slight warping in a few of the slides (particularly 4, 7, and 14, table 6) has decreased the accuracy of measurement. The component which shrinks to 11–12 Å on heating may be interstratified with a chloritic component, or partly chloritized, as described by MacEwan (1949). The mineral may include vermiculite layers. Whether montmorillonite is primarily interstratified with other layers or is a separate component is not known.

The following criteria were used for identification of minerals in the <2 micron fraction. Normal chlorites were identified by a 14 Å reflection which persists after heating to 550°–600° C., and by a 4.7 Å reflection (003). Antigorite is indicated by 7.3 Å and 3.63 Å reflections which are not destroyed by heat (MacEwan, 1951). Kaolinite is suggested in some samples by particularly strong 7.2 Å reflections which are not completely destroyed by hot HCl, accompanied by reflections at 3.59 Å, 2.39 Å (003), and in some cases 2.28 Å. Micas and illite are shown by basal reflections at about 10 Å and 5 Å. That most of the mica is dioctahedral is suggested by the relatively intense second order basal reflection. Montmorillonoid is identified in glycerol-saturated clay by the presence of an 18 Å reflection. Quartz is identified by a 4.27 Å reflection, and calcite by a 3.04 Å and associated reflections. The behavior of the 3.26 and 3.22 Å reflections under various conditions is not explained.

Clay from the <2 micron (unacidized) fraction of each loess sample was examined in a Philips EM-100 electron microscope. Electron micrographs are shown in plates 1 and 2.

LOESS SAMPLES FROM WESTERN EUROPE

For purposes of description the samples from western Europe will be discussed in six groups, each of which represents a geographic area. The first of these includes samples from near Torino, Italy, in Po River drainage, and the second from near St. Vallier, France, in the Rhone River Valley. Three groups are from areas in the Rhine Valley—namely the Strasbourg-Achenheim, France, area; from Mauer, near Heidelberg, Germany; and the Eltville-Wiesbaden, Germany, area. The sixth consists of a sample from Landen, west of Liége, Belgium.

Torino, Italy (Samples 1 and 2)

Two samples were collected from deposits exposed on the steep bluffs on the south side of the Po River and south of the city of Torino, Italy. The first of these was from near the crest of the bluff (sample 1), 500 meters west from Cavoretto along the road to Madalena. In this locality the Helvetian (Miocene) sandy silts contain a clearly recognizable soil profile in their uppermost part and are overlain by 2½ to three feet of loess. This thin loess contains in its uppermost part a reddish-brown soil with a well-developed B horizon. Nodular caliche extends downward into the Helvetian sediments below. Above this first loess soil is three to four feet of another loess with a soil in its upper part—less well developed than the lower loess soil, but reddish-brown in color and containing a caliche zone that extends downward into the A horizon of the lower loess soil. This second loess soil does not have strong textural contrast or well-developed structure in the B horizon but displays a strong color contrast within the profile. Above this second loess soil is exposed 12 feet of buff to yellow-tan coarse-textured loess, with indication that a greater thickness

TABLE 3.—*Lattice spacings and estimated intensities*

1		2		3		4		5		6		7		8		9		10	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
				16	w	16	w												
14.7	m	14.7	wm					14.7	m	14.7	m	14.7	ms	14.7	sm	14.7	m	14.7	wm
												12.6b	ww	12.6b	ww			12.8b	ww
10.2—	ss	10.2	s	10.3	s	10.2	s	10.3	ms	10.2	s	10.3	s	10.2	m	10.2	ms	10.3	s
7.31	mw	7.31	wm							7.31	.ww								
7.22	mw			7.28	w	7.25	w	7.25	s	7.22	m	7.22	s	7.25	ms	7.22	ms	7.25	s
5.02	m	5.03	m	5.05b	m	5.03b	s	5.03	ms	5.02	s	5.03	ms	5.01	ms	5.02	sm	5.03	s
4.84	mw	4.84	w					4.87	ww	4.84	w	4.84	w	4.90	w	4.84	ww	4.87	w
								4.79	w							4.75	w	4.79	w
																4.51	w		
				4.27	ww	4.29	ww	4.29	w	4.27	ww	4.29	w	4.29	mw	4.29	w	4.29	w
								4.19	w			4.21	w						
3.86	w									3.86	w					3.86	mw		
		3.64	ww	3.59	w	3.59	w	3.59	s			3.60	ms	3.59	ms			3.59	ms
3.56	mw	3.56	mw							3.57b	m					3.57b	m		
		3.48	ww											3.48	ww				
3.34	s	3.35	ms	3.36	m	3.34	s	3.36	s	3.34	s	3.36	s	3.36	s	3.35	s	3.36	s
3.26	w	3.28	w	3.27	w	3.26	ww					3.28	w	3.26	w	3.26	w	3.26	w
3.22	m	3.23	mw	3.21	w	3.22	ww					3.22	w			3.21	w	3.22	w
3.14	w																		
3.04	ms			3.05	ms	3.05	ww	3.05	mw	3.04	s	3.05	ms			3.04	ss	3.05	w

occurs under cover upslope. Although it is not known that a definite age determination of this loess has been made, Prof. Socin (personal communication) stated that it has yielded *Pupilla muscorum;* its stratigraphic and physiographic relations are judged to require an age no older than Würm, and do not preclude a late Würm age.

Sample 2 was collected from a road cut exposure part way down the steep bluff in the same vicinity. Here the loess rests directly on middle Helvetian (Miocene) with no intervening soil profile. The inclusion in its base of fragments of Helvetian rock, together with the field relationships, suggests that the deposit is at least in part colluvial and that the loess

TABLE 4.—*Lattice spacings and estimated intensities*

1		2		3		4		5		6		7		8		9	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
14.3	w	14.5	ww					14.5	m	14.3	w	14.0	w			14.5	m
13.0b	w	12.9b	mw	12.4b	w	12.6b	ww	13.0b	mw	12.9b	mw	12.8b	mw	12.4	m		
10.1d	ss	10.2	ss	10.2	s	10.3	s	10.3	s	10.2	ss	10.3	s	10.3	ms	10.2	ss
8.04b	w	8.18b	mw	8.46b	ww	8.42b	ww	8.1b	w	8.18b	mw	8.4b	mw	8.42b	mw		
7.31	m	7.31	m														
7.19	m	7.22	mw	7.25	w	7.25	w	7.25	s	7.19	wm	7.22	m	7.25	m	7.19	s
5.02	s	5.03	m	5.03	sm	5.04	ms	5.03	sm	5.03	ms	5.03	m	5.01	m	5.03	ms
4.84	m	4.84	m					4.87	w	4.87	w						
								4.77	wm	4.74	mw	4.77	mw			4.75	m
				4.27	ww	4.29	w	4.29	wm	4.28	w	4.28	w	4.29	mw	4.28	mw
								4.21	w			4.18	w				
3.63	w	3.62	w	3.59	w	3.60	w	3.60	s	3.59	wm	3.59	m	3.59	m	3.59	sm
3.54	m	3.53	m					3.56	ms	3.54	m	3.54	sm	3.52	m	3.55	ms
														3.49	w		
3.34	ss	3.34	s	3.35	s	3.35	s	3.36	ss	3.35	ss	3.35	s	3.35	s	3.35	ss
3.26	w	3.26	mw	3.26	w	3.28	w	3.26	mw	3.27	w	3.26	w	3.26	mw	3.26	mw
3.22	ms	3.22	m	3.22	w	3.23	w	3.23	mw	3.22	w	3.22	w	3.22	mw	3.22	mw
3.13	w	3.13	w							3.08	w						
								3.02	ww								
2.84	ww							2.83b	w	2.84	ww					2.84	mw
								2.70	w								
2.50	m	2.50	wm	2.51	mw	2.51	mw	2.51	wm	2.50	m	2.51	w	2.51	w	2.51	wm
								2.47	mw			2.47	ww	2.46	w	2.46	w
								2.39	wm	2.39	ww	2.39	ww	2.39	w	2.39	w
								2.29	mw					2.28	w		

diffractometer patterns of oriented loess (<2 microns)

11		12		13		14		15		Rawlins Co., Kans.		Gove Co., Kans.		Marshall Co., Kans.		Doniphan Co., Kans.	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
								15	m	15.5b	s	15.0b	s	15.5b	s	15.2b	ss
4.8	m	14.7	m	14.7	m	14.7	m										
0.2	s	10.2	s	10.2	s	10.2	m	10.2	m	10.2	m	10.2	m	10.2	s	10.3	wm
7.22	ms	7.25	s	7.22	s	7.22	ms	7.26	m	7.25	ms	7.25	m	7.25	m	7.25	ms
5.03	m	5.02	sm	5.03	m	5.03	m	5.03b	m	5.02	mw	5.02	w	5.03	m	5.03b	sm
4.84	w	4.87	w			4.82	w										
4.77	w			4.79	wm												
		4.53	w					4.52	ww								
4.48	ww					4.46	w										
4.27	mw	4.28	w	4.27	w	4.29	w	4.29	mw	4.28	mw	4.28	ww	4.28	wm	4.29	wm
4.17	w			4.21	w	4.18	w	4.21	w								
3.86	w	3.86	w	3.86	mw	3.86	mw			3.88	ww						
3.59	s	3.59	s	3.59	s	3.59b	m	3.60	sm	3.59	ms	3.59	mw	3.59	wm	3.59	ms
3.56	m					3.56b	wm										
		3.48	w									3.50	ww				
3.35	s	3.35	s	3.35	s	3.35	ms	3.36	s	3.36	s	3.35	s	3.35	s	3.36	s
3.26	w	3.26	w	3.27	mw	3.26	w	3.26	w	3.26	w	3.25	mw	3.26	w	3.26	w
3.23	w	3.21	w	3.22	w			3.21	w	3.21	w	3.21	mw	3.21	mw	3.21	w
3.04	ms	3.05	s	3.04	s	3.04	ss	3.05	m	3.05	sm	3.05	ms				

may have initially been deposited at a higher position on the slope. It is judged to be no older than Würm.

Mechanical analyses show that sample 1 (fig. 2) is the coarsest and best sorted of the European samples studied (table 1), whereas sample 2 has a finer average particle size and is not so well sorted.

Chemical composition of these samples is shown in table 2. Recalculation of the analyses to a $CaCO_3$-free basis showed that these samples have the lowest SiO_2 content and the highest MgO (particularly sample 1), K_2O (particularly sample 2), and Fe_2O_3 content.

The coarse fraction of both samples is characterized by unusually abundant muscovite. It also contains angular

diffractometer patterns of oriented, HCl-treated loess (<2 microns)

10		11		12		13		14		15		Rawlins Co., Kans.		Doniphan Co., Kans.	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
14.2	mw	14.5	wm	14.5	mw	14.5	m	14.5	m						
12.9b	w	13.2b	w					13.2b	w	12.8b	w	12.8	ss	12.6	ss
10.3	s	10.2	s	10.3	s	10.2	s	10.2	ss	10.2	s	10.3	m	10.3	s
7.22	ms	7.22	s	7.25	ms	7.19	s	7.22	ms	7.25	ms	7.25	sm	7.25	ms
5.03	ms	5.03	ms	5.03	m	5.03	ms	5.03	sm	5.03	m	5.03	wm	5.03	m
		4.84	w												
4.77	mw	4.74	wm	4.74	w	4.74	wm	4.74	mw						
4.48b	w											4.48b	w		
4.29	mw	4.28	mw	4.28	w	4.29	mw	4.28	mw	4.27	w	4.29	wm	4.29	m
3.60	m	3.59	ms	3.59	m	3.59	sm	3.59	m	3.59	m	3.59	ms	3.60	ms
3.56	m	3.55	sm	3.56	wm	3.55	sm	3.54	m						
												3.48	w		
3.35	s	3.34	ss	3.35	s	3.35	ss	3.35	s	3.35	s	3.36	s	3.36	s
3.26	w	3.26	mw	3.26	w	3.26	mw	3.26	m	3.26	w			3.25	wm
3.22	w	3.22	w	3.23	w	3.21	mw	3.21	m	3.20	w			3.21	wm
														3.01	w
2.84	ww	2.83b	w			2.84	w	2.84	w						
2.50	mw	2.50	m	2.51	mw	2.50	wm	2.50	mw	2.50	w			2.51	mw
2.47	w	2.46	w			2.46	w							2.47	mw
2.39	w	2.38	mw	2.39	w	2.39	mw			2.38	ww	2.39	mw	2.39	w
2.29	w	2.28	ww											2.29	w

TABLE 5.—*Lattice spacings and estimated intensities in diffractometer patterns of oriented glycerol-saturated loess (<2 microns)*

1		2[1]		3		4[1]		5[1]		6		7[1]		8		10		10[1]		12[1]		13		15		15[1]		Rawlins Co., Kans.	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
18b	w	18b	ww	18b	m	18b	w	18	mw	18b	mw	18b	w			18b	ww	18	ww	18	mw	18b	w	18b	wm	18	s	18	ss
14.5b	w	14.7b	ww					14.5	mw	14.7	w	14.5b	ww	14.5	m	14.6	ww	14.6	w	14.5	ww	14.7	w						
		13.0b	w			12.6	ww	12.8b	ww			13.2b	ww	12.6b	ww														
10.1	ss	10.2	ss	10.2	s	10.2	s	10.2	s	10.2	s	10.2	ms	10.2b	wm	10.2b	s	10.3	s	10.2	s	10.1	ms	10.2b	s	10.2	m	10.2	mw
																												9.2b	w
		8.2	w					8.11	w			8.3	w					8.11b	ww										
7.31b	mw	7.31	wm	7.31	w					7.22	wm	7.25	m	7.25	m	7.22	m	7.25	sm	7.25	sm	7.22	ms	7.25	ms	7.25	wm	7.25	m
		7.19	wm			7.25	w	7.22	s	5.03	m	5.03	sm	4.98	m	5.02	wm	5.03	sm	5.03	m	5.02	m	5.03	mw	5.03	mw	5.03	w
5.02	m	5.03	sm	5.03	m	5.03	m	5.01	sm			4.87	w	4.87b	m			4.87	w										
4.84	mw	4.87	mw					4.84	w	4.79	w	4.79	mw			4.77	w	4.77	mw	4.77	mw	4.74	w						
								4.74	wm	4.48	ww	4.53	ww					4.50b	w			4.49	ww					4.50b	w
				4.29	ww	4.28	ww	4.27	wm	4.29	ww	4.29	w	4.28	mw	4.29	w	4.28	mw	4.29	w	4.27	w	4.29	w	4.28	w	4.29	w
												4.19	ww									4.21	w						
		3.63	ww							3.88	w											3.86	w					3.88	w
		3.60	ww	3.59	w	3.60	w	3.59	sm			3.59	m	3.59	m	3.59	m	3.59	m	3.59	m			3.59	ms	3.59	m	3.59	m
										3.56b	m									3.56	m	3.57	ms						
3.54	mw	3.53	m					3.54	sm			3.54	sm					3.54	m					3.54	mw	3.53	mw		
				3.50	w							3.49	ww																
3.34	s	3.35	s	3.36	m	3.35	s	3.35	ss	3.35	s	3.35	s	3.35	s	3.36	s	3.36	s	3.35	s	3.35	s	3.36	s	3.35	s	3.35	s
		3.26	mw	3.26	w	3.26	ww	3.26	mw			3.26	w	3.26	w	3.27	w					3.25	w	3.26	ww	3.26	w		
3.21	m	3.23	wm	3.23	w	3.22	ww	3.21	mw	3.24	ww	3.23	w			3.22	w					3.22	w	3.22	ww	3.21	ww		

[1]Acid treated.

quartz, some biotite, and a bronze-colored mica probably representing altered biotite; some schist fragments and traces of chlorite. Sample 1 has coarse calcite grains but sample 2 has none.

X-ray diffraction data from the <2 micron fraction show that the clay minerals are predominantly muscovite, a 14.5 Å mineral, calcite (in sample 1) and antigorite (fig. 3). There is little or no detectable quartz or kaolinite. The 14.5 Å mineral (or minerals) is shown by glyceration and heat treatment to be perhaps in part chlorite, in part montmorillonite and in part a mixed-layer mineral. There is some possibility that the montmorillonite in these and some of the other samples may be a dioctahedral variety such as that described by MacEwan (1954). No superlattice reflections were observed at low angles. The 12 Å reflection formed by heat treatment does not shift after the preparation has been exposed to humid air for several weeks. The 10 Å and 5 Å reflections in sample 1 are particularly sharp, and the 10 Å reflection has a shoulder on the high-angle side which suggests the presence of two 10 Å minerals.

Electron micrographs show that sample 1 consists predominantly of very thin, clearly defined, smooth flakes (ground mica?), many of which have minute rods and shreds along their edges (pl. 1A). There are also larger rods, some straight-sided and some jagged. The particles of sample 2 are also flaky, but the flakes are puffier and less distinct. The tiny shreds are not present (pl. 1B). No fibers typical of chrysotile were observed in either 1 or 2.

The high MgO and Fe_2O_3 con-

TABLE 6.—*Lattice spacings and estimated intensities in diffractometer patterns of oriented loess (<2 microns) heated to 550°–600° C. for 30 minutes*

1[1]		2		3[1]		4		5		7		8[1]		9		13[1]		14	
d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I	d	I
14.2	m	14.2	w	14.5	w			14.2	w	14.1	w	14.5	w	14.0	mw	14.2	m	13.8	w
12.3	mw	12.3	m	11.2b	w	11.3b	w	12.1b	ww	11.9	w	11.5b	w	11.8b	ww			12.1b	ww
10.1	ss	10.2	ss	10.2	s	10.2	s	10.2	s	10.2	ss	10.3	s	10.1	s	10.3	ss	10.1	ms
7.31	wm	7.34	mw													7.19	w		
5.02	s	5.03	sm	5.03	m	5.04	sm	5.03	ms	5.03	ms	5.09	ms	5.02	m	5.05	ms	5.01	m
4.90	m	4.90	w																
				4.27	w	4.27	w	4.28	w	4.27	w	4.29	wm	4.50	w	4.29	mw	4.48	ww
														4.27	w			4.27	w
														3.85	ww			3.85	w
3.62	mw	3.63	ww					3.52	w					3.52	ww				
								3.36	s					3.35	s	3.35	ss		
3.34	ss	3.35	s	3.35	s	3.35	s	3.26	m	3.35	s	3.36	ss	3.35	s	3.26	m	3.35	s
3.25	sm	3.26	m	3.25	m	3.26	m			3.28	m	3.26	sm	3.25	m	3.22	mw	3.25	wm
3.13	w																		
								3.04	w	3.04	w			3.04	ms			3.03	s
2.50	m	2.50	w	2.51b	wm	2.52b	wm	2.51	m	2.52	wm	2.53	m	2.52	mw	2.51b	wm		
												2.47	w	2.49	mw			2.49	wm
												2.28	w	2.28	wm			2.28	m

[1] Acid treated.

tent, the presence of chlorite and antigorite, and the large quantities of mica suggest that the source material consisted largely of serpentine, mica schist, and probably basic igneous rocks. Such source rocks in a position tributary to the Po River at this point are indicated by the geologic maps of Hermann (1937; 1937a). These maps indicate the close proximity of serpentine (sometimes with important relics of ultrabasic rocks), peridotite with diverse associated ultrabasic rocks, and mica schist, gneiss, and granite at progressively greater distances. The loess was derived either directly from these igneous and metamorphic rocks or indirectly from reworked material in the Helvetian sediments. Antigorite, which is not observed in the other loesses studied, seemingly came from the serpentine bedrock. It is worthy of note that Antigorio Valley, from which antigorite was named, is near by in the Piedmont Division.

St. Vallier, France (samples 3 and 4)

Samples 3 and 4 were collected from exposures in an excavation made for the collection of vertebrate fossils between St. Vallier and St. Uze, France, on the east side of the Rhone River Valley south of Lyon (fig. 1). Here sand, gravel, and silt mantle granite bedrock and form the surface of a high terrace approximately 250 feet above the Rhone River. The upper, silty part of these deposits has yielded a large and distinctive fauna of fossil vertebrates dated as Villafranchian (personal communication, Prof. F. Schaub, Basel, and Prof. Jean Viret, Lyon). A mature, brownish soil is developed in the eroded surface of these fossiliferous silts (pl. 3A). This buried soil is overlain by three to six feet of loess that immediately underlies the surface and contains the surface soil. The modern surface soil developed in this loess is less well developed than the buried profile formed in truncated Villafranchian

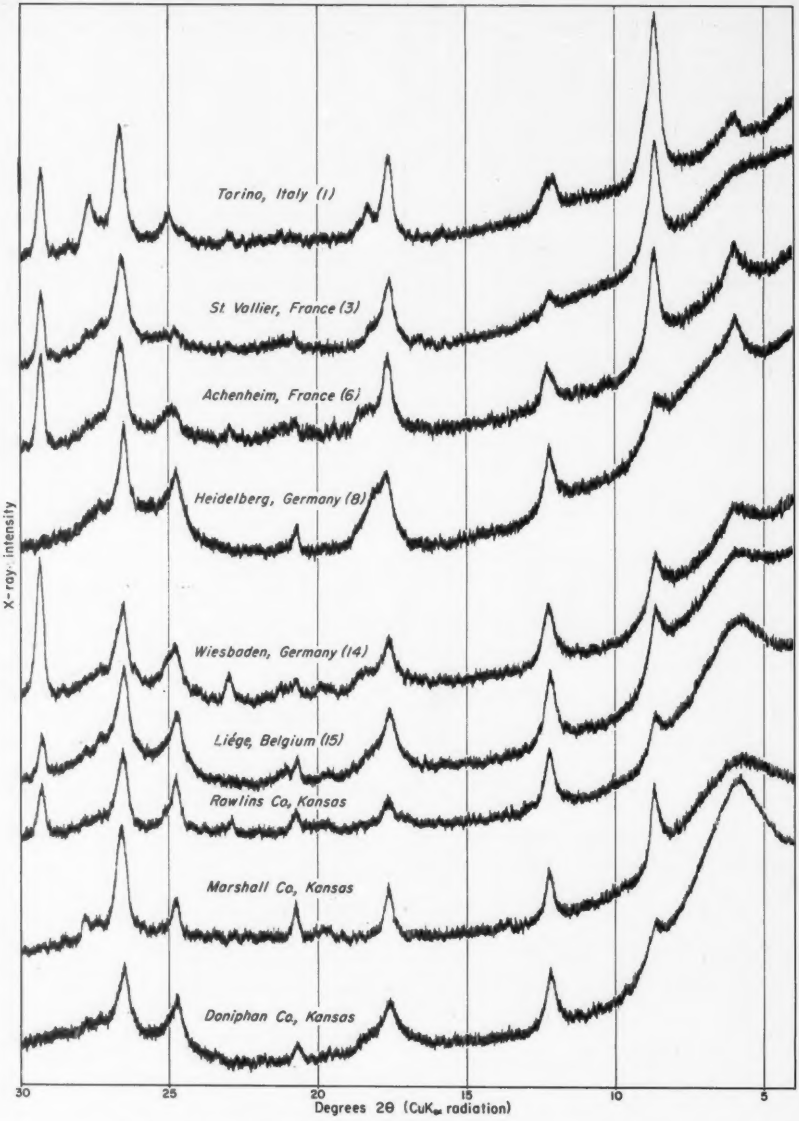


FIG. 3.—X-ray diffractometer patterns of minus two micron fraction of loess oriented on glass slides.

deposits. Although no direct dating for the loess is available to us, the degree of profile development suggests a late Pleistocene age (Riss or Würm) for the surface loess at this locality. Sample 3 was taken below the modern soil profile but more than a foot above the top of the buried soil, whereas sample 4 was taken just above the top of the buried soil, or from the basal few inches of the loess.

Mechanical analyses show that sample 3, although having a rather fine average particle size, is well sorted (fig. 2; table 1). Sample 4 is more poorly sorted, having a few grains coarser than one mm and 13 percent finer than one micron.

Except for low MgO content, the chemical composition is similar to that of several other loess samples. Sample 3 is highly calcareous, whereas sample 4 is only moderately so (table 2).

The fraction coarser than 44 microns contains angular quartz, moderate amounts of muscovite and biotite, less than five percent feldspar (chiefly potassium feldspar), and traces of weathered granite or granite gneiss. Calcite grains are common in sample 3. Sample 4 contains little calcite but much limonite. No chlorite flakes were observed in the coarse fraction.

The minerals in the <2 micron fraction are chiefly illite (or illite and muscovite) and an expanding montmorillonite mineral which has a very broad reflection at 15 to 16 Å which shifts to 18 Å+ with glycerol (table 5). After heating to 550°–600° C., there is a suggestion of a reflection at 11.3 Å, indicating that the expanding mineral is not pure montmorillonite. Small quantities of quartz and possibly kaolinite (001, 002) were observed. There is no 14 Å chlorite or vermiculite. There are moderate quantities of calcite in the fine fraction of sample 3, and only traces in sample 4.

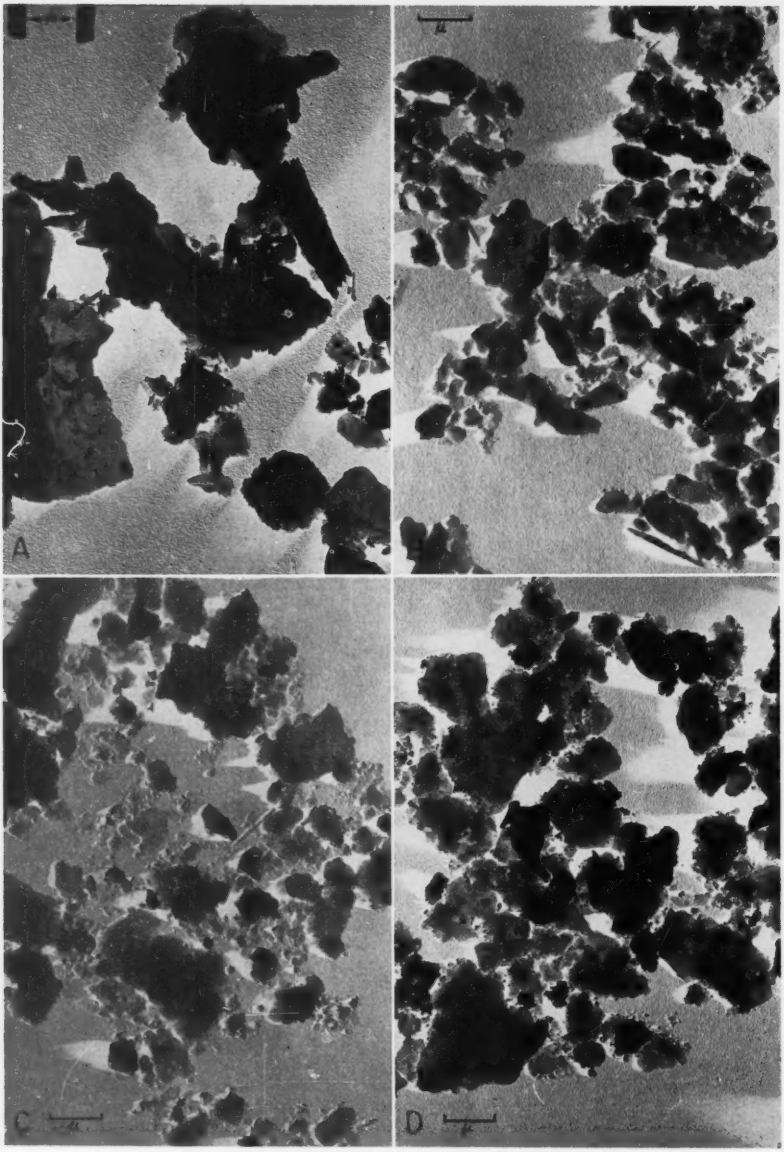
In the electron microscope samples 3 and 4 are seen to consist predominantly of rather flat irregular flakes, a very few of which have a cottony appearance (pl. 1C). There are essentially no rods. In sample 4 some of the flakes are slightly shredded at the edges.

The angular quartz, potassium feldspar, muscovite, and biotite, and absence of chlorite-vermiculite suggest that the ultimate source was, at least in part, near-by siliceous crystalline rocks.

Strasbourg-Achenheim, France (samples 5 and 6)

In the vicinity of Strasbourg, France, loess samples were obtained from brickpit excavations on an intermediate terrace of the Rhine (sample 5) and from the extensive high terrace of the Rhine (sample 6). The sample from the intermediate terrace (pl. 3B) was taken about six kilometers southwest of Strasbourg. The section exposed here consists of fossiliferous loess, which was sampled, resting on a soil developed in alluvial sands and gravels; this loess possesses a weak soil profile and in turn is overlain by a younger loess. The loess sampled was dated as early Würm (personal communication, Prof. Dubois and Dr. Wernert).

The large brick pits at near-by Achenheim yielded the sample of oldest loess obtained in the Rhine Valley (sample 6). This loess has been dated as late Mindel or "Anti-penultimate glacial 2" (Zeuner, 1946), and more recently (Zeuner, 1952) as "Penultimate glacial" or Riss age. The loess, which is gray and contains fossil snail shells, occurs above a soil developed in the uppermost part of thick, gray sands tentatively correlated with the Mosbacher sands (which also contain fossil snails) and is overlain with seeming conformity by red sands that contain a buried soil in their top. This upper sand is overlain by another loess that has been correlated with the Würm deposits of the intermediate terrace (personal communication, Prof. Dubois and Dr. Wernert), and the thick sequence of "older" loesses that wedge out against the truncated terrace front (missing in the main terrace) belong in age between the red sands and the youngest loess that blankets the entire area.


A
C
D

Sample 6 has a particle size distribution and sorting typical of many other loess samples studied (fig. 2). Sample 5 is unusually clayey, having 28 percent finer than one micron.

In chemical composition, sample 6 is distinguished by the highest TiO_2 content of all the samples (when calculated on a carbonate-free basis). It also contains the most $CaCO_3$ (40.69 percent). Both samples are fairly high in MgO.

In sample 5 the fraction coarser than 44 microns contains angular to well-rounded quartz, perhaps 30 percent feldspar (chiefly K-feldspar), and only a small quantity of mica and calcite. Sample 6, on the other hand, contains larger quantities of rounded quartz grains with common limonitic stain. The feldspar content is less than five percent. There are several grains of chert or chertlike aggregates, and there is much muscovite, biotite, and chlorite, plus a trace of schist and phyllite. Finely crystalline calcite is extremely common in sample 6.

X-ray diffraction data show that in the fraction finer than two microns there are also several differences between samples 5 and 6. The clay fraction from sample 6 contains much calcite, whereas the clay from the younger loess contains only a small quantity (<five per cent). Sample 5 contains primarily a 14.7 Å mineral and kaolinite (001, 002, and 003 reflections prominent), with only a small quantity of 10 Å clay. Asymmetry of the 10 Å reflection suggests that the mineral is in part mixed-layer. Sample 6 contains chiefly illite (10 Å mineral) and a 14.7 Å mineral, with only a small quantity of kaolinite (fig. 3). Both samples contain small amounts of quartz. The behavior of the 14.7 Å reflection in both samples is similar to that in most of the other loesses. It includes a montmorillonite component (18 Å with glycerol), chlorite (14.2 Å reflection present after heating), and seemingly a partly chloritized mixed-layer component (12.1 Å reflection after heating).

Electron micrographs of sample 6 show very thin, large, flat, irregular flakes (pl. 1D), and many minute dense specks (calcite?) having diameters of the order of magnitude of 0.03 microns or smaller. Some of the specks seem to have rodlike shapes, but others do not.

A source for all the materials found in these two samples may be assigned to the drainage basin of the Rhine above Strasbourg. Some of the petrographic differences between the Riss and Würm loesses in this area are perhaps accounted for by the greater extent of the Alpine Riss glaciers which transgressed significantly onto the Jura Mountains.

Heidelberg, Germany (samples 7 and 8)

At the Grafenaien pit at Mauer, near Heidelberg, Germany (that yielded the widely known Heidelberg jaw), a succession of loesses (pl. 3C) occurs above the sands and gravels (Zeuner, 1952). These deposits are in an abandoned loop of the Rhine River, and at the locality studied a well-developed soil occurs in the top of the sands and gravels below the oldest observed loess. A comparably well-developed soil caps this loess, and a relatively thick section of loess containing an abundant snail fauna occurs above the soil. The upper loess contains locally a thin red clay streak that presumably marks the division between Zeuner's

---

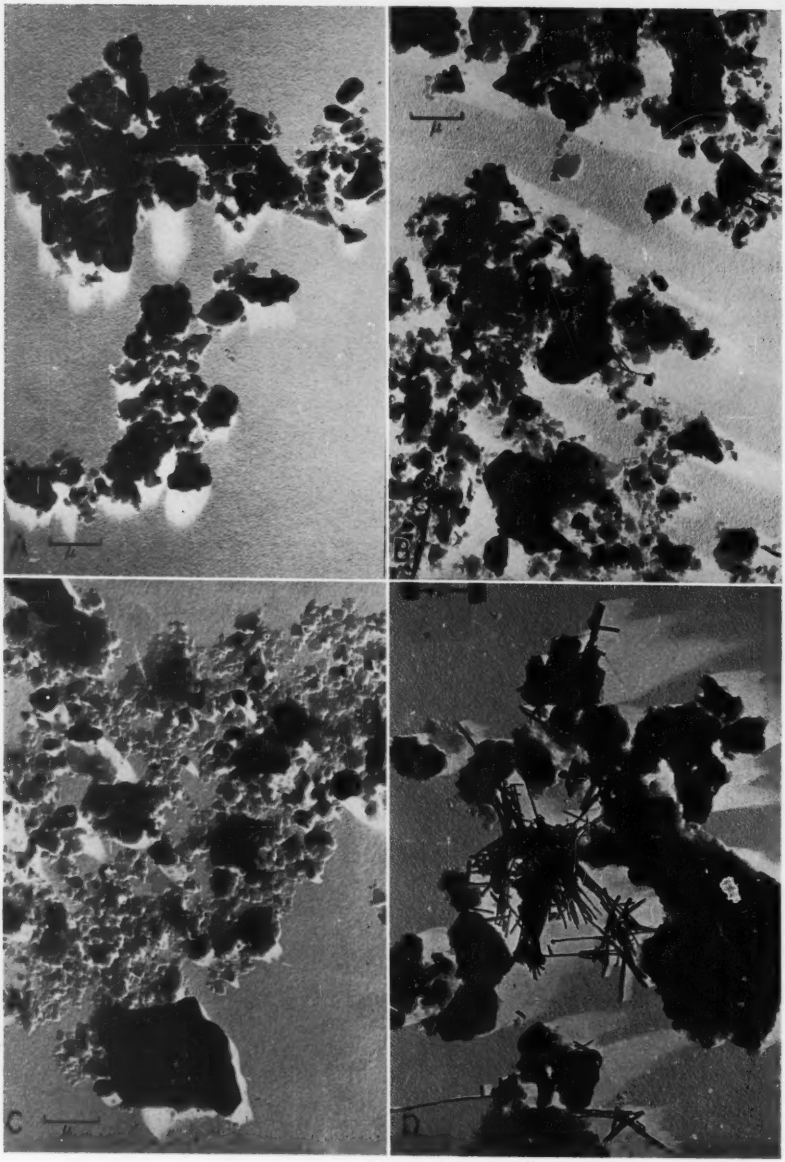
PLATE 1.—Electron micrographs of minus two micron fraction of loess, shadowed with chromium at 20°, from Italy and France.

A.—Sample 1 from near Torino, Italy. Note sharply defined flakes and a few small rods.

B.—Sample 2 from near Torino, Italy. Note irregularity of flakes in contrast to A, and virtual absence of rods.

C.—Sample 3 from near St. Vallier, France, showing presence of fluffy masses judged from X-ray diffraction patterns to be montmorillonite.

D.—Sample 6, oldest loess exposed at Achenheim, France, characterized by thin, flat flakes.


A
B
C
D

(1952) Younger Loess I and Younger Loess II. Sample 7 was taken from the lower part of this upper loess and is clearly assignable to the Würm. Sample 8 was from below the well-developed soil and presumably is Zeuner's "Upper Older Loess" and of Riss age; however, it seems a possibility that sample 8 is from a loess of early Würm age.

Mechanical analyses show that the two samples are rather fine-grained with moderate admixtures of sand.

In chemical composition, sample 8 has the highest SiO_2 (81.25 per cent on a carbonate-free basis) and the lowest Fe_2O_3. It is also low in MgO. Otherwise these samples are not unusual.

The fraction coarser than 44 microns is limonitic; sample 8 contains much dark-brown limonitic plant material as well as the limonite stain which is also common in sample 7. Both samples contain rounded to angular quartz grains. Sample 7 contains about 25 percent feldspar (predominantly K-feldspar), a few granite fragments, and very little coarse mica. It also contains many calcite grains. Sample 8 has only moderate amounts of feldspar and no calcite, but more mica than sample 7.

In the fraction finer than two microns, samples 7 and 8 are similar except that sample 7 contains a moderate amount of calcite and sample 8 has none (fig. 3). The minerals other than calcite are chiefly a 14.7 Å mineral, illite, and kaolinite, plus a small quantity of quartz. Sample 8 contains less 10 Å mineral than does sample 7, even though it has more mica in the coarser fractions. Broad, weak 12–13 Å reflections were observed in both samples. The behavior of the 14.7 Å reflection in both clays is similar to that in the clays previously described (tables 4, 5, 6).

Electron micrographs of the <2 micron fraction show that sample 8 contains many very small, flaky particles having generally somewhat poor crystallinity (pl. 2A).

Eltville-Wiesbaden, Germany (samples 9, 10, 11, 12, 13, and 14).

In the region of Eltville and Wiesbaden, west of Frankfurt, loess samples were collected in three localities: (1) samples 9 and 10 from road cut exposures in the vicinity of Eltville; (2) sample 11 from a brick-pit exposure at Eltville; and (3) samples 12, 13, and 14 from exposures in the Dycherhoff pit at Wiesbaden.

In the road cuts near Eltville the loess is thin and occurs on the surface of the highest of the middle terraces of the Rhine Valley. At the locality of sample 9 a Würm I–II interstadial Brown soil developed in Oligocene sediments is well exposed and the sample was taken from the Würm II loess (personal communication, Dr. Ernst Schonhals). About 200 yards from the above exposure a deep Chernozem soil developed in the top of Riss loess is exposed in a small excavation where this soil is overlain by Würm I and II loess (personal communication, Dr. Schonhals). Sample 10 is from the lower part of the A horizon of this soil.

In a brick pit near Eltville approximately 30 feet of tan loess is well exposed. Dr. Ernst Schonhals (personal communication) has classed the exposed material as Würm I, II, and III on the basis of a relatively weak lower soil and a calcareous humic band at a higher posi-

---

PLATE 2.—Electron micrographs of minus two micron fraction of loess, shadowed with chromium at 20°, from Germany, Belgium, and Kansas.

A.—Sample 8 from the Grafenaien pit at Mauer, near Heidelberg, Germany.

B.—Sample 14 from the Dycherhoff pit at Wiesbaden, Germany. Note relative abundance of rods.

C.—Sample 15 from Landen, west of Liége, Belgium, showing presence of fluffy masses judged from X-ray diffraction patterns to be montmorillonite.

D.—Sample from Gove County, Kansas (Swineford and Frye, 1951), showing abundant rods and montmorillonite masses.

tion. A thin zone of volcanic ash (one inch ± thick) is reported by Dr. Schonhals to occur in the Würm II zone but it was not observed at the time of our visit to the pit. The loess here, as at the other Eltville locality, occurs on a "Middle" terrace of the Rhine Valley. Sample 11 was taken from the Würm II zone.

In the Dycherhoff pit at Wiesbaden extensive exposures were examined. Aquitanian marls and some lignite constitute the lower part of the section; these are locally overlain by quartz sand and pebbles classed as Villafranchian in age (personal communication, Dr. J. Bartz), which are unconformably overlain by sand and gravel of the Rhine Valley terrace, classed as Mosbacher. The surface of the gravels displays an erosional unconformity which is overlain by a continuous mantle of relatively thin loess classed by Dr. Ernst Schonhals (personal communication) as Würm. A well-developed Brown soil is at the surface and sample 12 is from the C horizon of this soil, whereas samples 13 and 14 are from about two feet below the base of the soil profile.

Mechanical analyses of samples 9 to 14 show that these loesses are rather poorly sorted, particularly toward the coarse end of the particle size distribution. One of them (sample 11) contains 1.1 percent coarser than two mm. The fraction finer than one micron of five of the six samples ranges from 8.9 percent to 12.7 percent, whereas sample 10 (from the Riss A horizon) contains 18.2 percent finer than one micron.

The coarse fractions are mineralogically more variable from sample to sample than are the finer fractions and probably reflect local lithology along the Rhine graben. Feldspar content ranges from five to 33 per cent and is highest in samples 12 to 14. Where feldspar is low, schist and phyllite content is high; one sample (11) contains more than 50 per cent metamorphic rock fragments in the coarsest fraction (>250 microns). Most of the quartz is angular, although rounded grains are present in several samples. Some vein quartz was observed. All samples contain calcite grains; sample 14 has the most and samples 10 and 12 the least. The calcite of sample 10 has spherulitic structure and is probably caliche from the overlying Würm loess. Muscovite, biotite, and chlorite are present in most samples. Although volcanic ash is reported at the Eltville locality, no volcanic glass was observed in the samples.

In all the Eltville-Wiesbaden samples, the fraction finer than two microns is characterized by a 10 Å mineral (mica, illite), a 14.7 Å mineral, and small quantities of kaolinite and quartz. Calcite content is variable, sample 14 containing the most and sample 10 the least. The greatest variation among the six samples is in the behavior of the 14.7 Å reflection. Sample 9 shows no indication of montmorillonite on saturation with glycerol, whereas the other samples show weak 18 Å reflections. Sample 10 (the A-horizon sample) is unique in showing a weak 12 A band, which may perhaps be attributed to a hydrobiotite-type mineral. Sample 12 contains somewhat less chloritic component than do the other samples of this group. In sample 13, heat treatment produced the best 14 Å reflection of any sample in the Eltville-Wiesbaden group, and it is the only loess having a 14.7 Å reflection which does not show a 12 Å reflection on heating. There is also a residual 7.19 Å reflection (chlorite 002?) in sample 13 after heat treatment.

Electron micrographs show many elongate particles or rods in samples 9, 12, 13, and 14. Most of these particles are not straight-sided, and at high magnifications some of them are seen to be flat with angularly jagged sides. Their composition is not known. In general, the micrographs show mixtures of several types of particles, mostly flaky and well crystallized, some having 120° angles (pl. 2B).

The source of the loess of this area presumably lies in the widely diversified

rocks that occur in the drainage basins of the Rhine and Main Rivers above Wiesbaden, whereas samples 7 and 8 from near Heidelberg should reflect a source predominantly from the upper Rhine basin. Although shifting source of gravels in this area is indicated by the lithologic contrast between the Villafranchian and Mosbacher gravels in the Dycherhoff pit (Dr. F. Bartz, personal communication) it is judged that the Rhine, as the major outwash-carrying stream during late Pleistocene time, furnished the predominant source for the loess of the region.

Landen-Liége, Belgium (sample 15)

Loess exposures were examined from the vicinity of Liége to Louvain in Belgium. Sample 15 was taken from the face of a brick pit at Landen where about eight feet of calcareous loess was exposed in a planed face. The sample was taken about six feet below the top of the pit, which is approximately at the general upland level. Although some cryoturbation features were observed in this exposure they were much less prominent than in near-by exposures studied. The loess at this locality is tentatively assigned to the Würm (Prof. F. Gullentops, personal communication).

Mechanical analysis of sample 14 shows that it is well sorted and typical of other fine-grained loesses studied (fig. 2).

Chemical analysis shows that this sample is rather high in SiO_2 (80.80 per cent on a carbonate-free basis) and lowest of all samples in Al_2O_3. It also is low in Fe_2O_3 and MgO (table 2).

The fraction coarser than 44 microns consists predominantly of angular to subrounded quartz with limonite stain. There is much muscovite and some biotite in the finer sizes, but no very coarse mica and only a small quantity of feldspar. Some calcite is present.

The fraction finer than two microns contains montmorillonite, illite (and mica?), and kaolinite, with small quantities of calcite and quartz. There is more montmorillonite than in any of the other European loesses studied (table 5). The 10 Å and 5 Å reflections are broad, suggesting the presence of poorly crystalline illite. No chlorite or vermiculite reflections were observed.

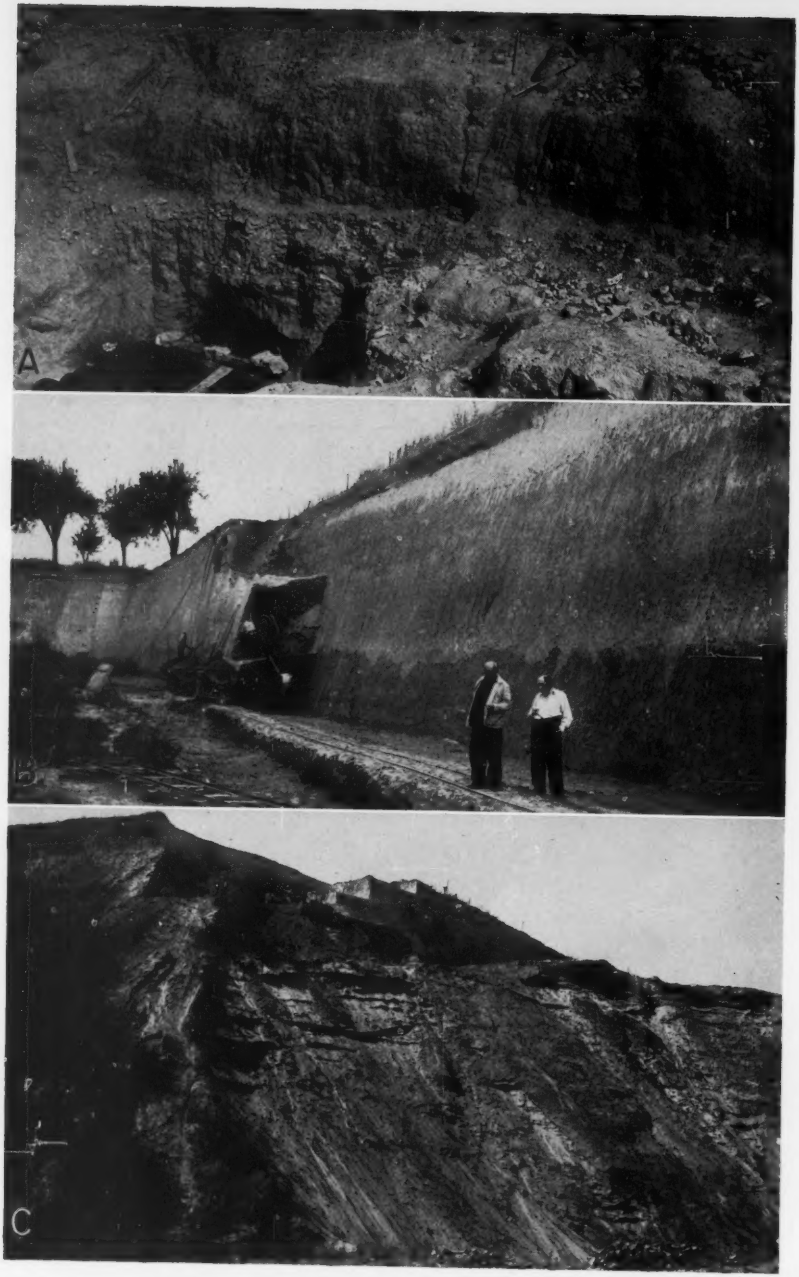
Electron micrographs show much fine-grained, poorly crystallized, almost cottony material suggestive of montmorillonite (pl. 2C). There are also a few long, straight-sided laths.

The loess at Landen occurs in an upland situation not closely associated with a major outwash-carrying stream. Its source therefore is more difficult to localize than that of the other samples studied. The relatively great abundance of montmorillonite, however, together with limonite stain on the quartz grains, low feldspar, absence of chlorite, and relatively abundant kaolinite, suggest a source, in part at least, in a deeply weathered region rather than outwash or valley train material from glacially abraded crystalline rocks.

SUMMARY OF PETROGRAPHY OF KANSAS-NEBRASKA LOESS

The petrography of Kansas loess has been described in some detail by Swineford and Frye (1951). Median diameter ranges from 4.29ϕ (0.051 mm) to 5.59ϕ (0.021 mm) in 47 mechanical analyses of loess from this region; the sorting, as shown by the phi quartile deviation, ranges from 0.36ϕ to 0.89ϕ. The range in median diameter is only slightly more than one Udden grade, but it displays a high degree of geographic consistency.

In the fraction coarser than 44 microns the major constituents were determined to be quartz, feldspar, volcanic ash shards, carbonates, and some micas. Feldspars (potassium feldspars being prevalent) are the second most abundant mineral group and occur generally in a ratio to quartz of 1:4. Volcanic ash shards were observed in all samples stud-


A
B
C

ied, but their abundance ranges from a trace to as much as 10 percent of the coarse silt fraction. Some fresh shards were found in all samples, but many were altered, particularly at the margins. Micas generally constitute only about three percent of the coarse silt fraction and consist of muscovite with some biotite. Small quantities of chlorite are also present. Chert is present in the samples from along the Missouri River Valley but is rare to absent in samples from the High Plains. Some silt-size grains of calcite and dolomite also occur in samples taken along Missouri River whereas only calcite was found in samples from farther west.

Chemical analyses indicate that Kansas loesses are relatively high in Al_2O_3 and alkalies, but low in CaO.

In order to make proper comparisons with X-ray data from the European samples, four Kansas samples from Rawlins, Gove, Marshall, and Doniphan Counties, Kansas, were analyzed during this study. The clay minerals of the fraction finer than two microns are predominantly montmorillonite, with minor quantities of illite and kaolinite. This mineralogy is common in the loess throughout Kansas, Nebraska, South Dakota, and southwestern Iowa (Mielenz, Holland, and King, 1949; Davidson and Handy, 1953). All samples studied contain quartz. There is no evidence of chlorite or vermiculite. Samples from Rawlins and Gove Counties in western Kansas contain moderate quantities of calcite. The Marshall County loess contains none. The Doniphan County loess, although containing carbonate in the coarser fractions, has no detectable calcite in the <2 micron fraction. The Marshall County loess contains more illite than do the other Kansas loesses studied. Some of the diffraction patterns show a faint suggestion of a trace of feldspar.

Electron micrographs of particles finer than two microns from Kansas loess samples show many large, cottony aggregates (montmorillonite) and some flat flakes. Calcareous loess from western Kansas contains many long, uniformly narrow rods (pl. 2D) which are readily soluble in acetic acid.

Kansas loess is largely derived from the flood plains of the major outwash-carrying streams during late Pleistocene time, particularly Platte River in Nebraska north of Kansas and Missouri River along the northeastern edge of the state (Swineford and Frye, 1951). The Platte River source reflects the crystalline rocks of the Rocky Mountains eroded by late Pleistocene glaciation, and Cretaceous and Tertiary sediments contributed by side-stream action; whereas the Missouri River source was importantly influenced by material from the late Pleistocene continental glaciers to the north.

CONCLUSIONS

Judging from the localities studied in western Europe the field appearance of loess in that region is similar to that of the central Great Plains. The buried soils (or paleosols) examined were surprisingly similar to those of the Great Plains region, not only in great soil groups but also in degree of development,

---

PLATE 3.—Some sample localities in western Europe.

A.—Locality of samples 3 and 4 near St. Vallier, France. Pit (covered with boards) in lower part of view has yielded Villafranchian vertebrate fauna (personal communication from Professors Jean Viret and F. Schaub), and these deposits terminate upward in buried soil. Loess samples from above buried soil.

B.—Locality of sample 5, brick pit in early Würm loess (personal communication from Prof. Dr. Dubois and Dr. Wernert, shown in photo) on intermediate terrace of Rhine Valley, near Strasbourg, France.

C.—Locality of samples 7 and 8; Grafenaien pit at Mauer, near Heidelberg, Germany. The Pleistocene gravel of this pit, which yielded the Heidelberg jaw, is capped with a succession of loesses and buried soils.

color, textural contrast, and structure. It is worthy of note that the term "loess" is used by some workers in western Europe to include deposits of various origins (e.g., Achenheim) that have the appearance of massive silt, but the samples reported here were collected from beds that were judged to be predominantly eolian in origin, either from field relationships, presence of buried soil, etc., or by the statement of a local expert.

In general the European samples studied have the same size and sorting characteristics as Kansas loess (fig. 2). They differ in having more clay in the finer fractions and generally more and coarser sand in the coarser fractions. In the European samples the sorting is less perfect and the skewness is also greater. Sample 1 from near Torino, Italy, is virtually identical with some samples of Kansas loess in texture, even though the mineralogy is quite different.

Chemically, the Kansas loess is generally similar to the European loess analyzed (table 2), although it is relatively high in Al_2O_3 and alkalies and low in CaO.

The size fraction of the Kansas loess coarser than 44 microns is distinctly more uniform in composition geographically than this fraction from the European samples. This difference is judged to be a result of the diversified and local source areas for the European samples, although they lie within a rectangular area substantially smaller than the State of Kansas. Volcanic ash shards invariably occur in this fraction of the Kansas samples but none were found in any of the European samples.

In the size fraction smaller than two microns Kansas loess is notable for its montmorillonite whereas most of the European samples have a 14.7 Å chlorite-vermiculite? mineral which is thought to be derived from altered basic igneous rocks. In many of the European samples the 10 Å reflection is sharp and may be produced by finely divided micas rather than illite. Kansas loess has somewhat more quartz in the fine fraction than do most of the European samples studied.

In the electron microscope (pls. 1 and 2) the Kansas material has a notably different appearance because of the prevalence of large cottony areas (montmorillonite), which are lacking in most of the European samples. Small rodlike particles are present in both the Kansas and European samples. The Kansas rods are long, straight-sided, and relatively uniform in size, and occur in clusters; whereas the rods observed in the European samples lack these characters and display many varied forms. The European samples commonly show flat, well-crystallized flakes.

The most significant conclusion of the study is that materials in widely separated regions that possess so much similarity in field appearance, topographic relationships, soil profile development, texture, and stratigraphy display such strong differences in mineralogy. Obviously the contrast in mineralogy in the coarse fraction reflects the source, and it is our judgment that source has exerted the controlling influence on the fine fraction as well. As the clay minerals found in the lower A horizon of an interglacial soil (sample 10 near Eltville, Germany) are essentially the same as those found in adjacent fresh loess, it may be argued that the clay minerals did not develop in the loess but were produced by a prior period of weathering or alteration of the source rock or were transported in an unaltered condition from the source rock. The strong contrast in the montmorillonite content seems clearly attributable to the presence of abundant volcanic glass both in the Kansas loess (where it may have altered to clay in place) and in the source rocks to the northwest which contain both volcanic glass and bentonites, as it has been pointed out (Grim, 1953) that montmorillonite is not an abundant mineral in the glacial deposits of North America.

REFERENCES

DAVIDSON, D. T., and HANDY, R. L., 1953, Studies of the clay fraction of southwestern Iowa loess (abstract): Abstracts of Papers Presented at the Second Conf. on Clays and Clay Minerals, Columbia, Mo., p. 4.

FRYE, JOHN C. and LEONARD, A. BYRON, 1951, Stratigraphy of the late Pleistocene loesses of Kansas: Jour. Geology, v. 59, pp. 287–305.

———, 1952, Pleistocene geology of Kansas: Kansas Geol. Survey Bull. 99, pp. 1–230.

FRYE, JOHN C., PLUMMER, NORMAN, RUNNELS, R. T., and HLADIK, W. B., 1949, Ceramic utilization of northern Kansas Pleistocene loesses and fossil soils: Kansas Geol. Survey Bull. 82, pt. 3, pp. 49–124.

GRIM, RALPH E., 1953, Clay mineralogy. McGraw-Hill Book Co., Inc., New York, 384 pp.

HERMANN, F., 1937, Carta geologica delle Alpi Nord-Occidentali; Foglio E: Arti Grafiche Moreschi & C., Milano.

———, 1937a, Carta geologica delle Alpi Nord-Occidentali; Foglio W: Arti Grafiche Moreschi & C., Milano.

MACEWAN, D. M. C., 1949, Some notes on the recording and interpretation of X-ray diagrams of soil clays: Jour. Soil Sci., v. 1, pp. 90–103.

———, 1951, The montmorillonite minerals (montmorillonoids): X-ray identification and crystal structures of clay minerals: Mineralogical Soc., London, pp. 86–137.

———, 1954, "Cardenite," a trioctahedral montmorillonoid derived from biotite. Clay Minerals Bull., v. 2, pp. 120–126.

MIELENZ, R. C., HOLLAND, W. Y., and KING, M. E., 1949, Engineering petrography of loess (abstract). Geol. Soc. America Bull., v. 60, p. 1909.

SWINEFORD, ADA and FRYE, JOHN C., 1951, Petrography of the Peoria loess in Kansas: Jour. Geology, v. 59, pp. 306–322.

ZEUNER, F. E., 1946, Dating the past. Methuen and Co., Ltd., London, 444 pp.

———, 1952, Dating the past, Methuen and Co., Ltd., London, 495 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 24–37
FIGS. 1–10, MARCH, 1955

MARINE SEDIMENTS NORTH OF SCRIPPS SUBMARINE CANYON, LA JOLLA, CALIFORNIA

C. STANLEY WIMBERLEY
2507 North Boulevard, Houston, Texas

ABSTRACT

Part of La Jolla Bay is occupied by five geographically distinct sediment types, based upon grain size. An isolated area now under forty fathoms of water contains coarse particles suggestive of a former beach on the rim of La Jolla Submarine Canyon; the other four types display a strikingly linear correlation of grain size with depth of water, represented by the following equation:

$$\text{Mud Percentage} = 1.74 \times (\text{Depth in fathoms}) - 1.93.$$

A sharp change in mud percentage is found at thirty fathoms, which may correlate with the seaward limit of eddy water movements near shore.

The sands consist chiefly of subangular quartz and abundant feldspar. The widely different hydraulic properties of mica and dark minerals are shown by their correlation with depth. Organic remains are uniformly distributed.

The apparent absence of a submarine canyon offshore from a prominent land valley suggests that the forces which clear and preserve two submarine canyons on the south are lacking farther north.

INTRODUCTION

Just north of La Jolla, California, Scripps and La Jolla Submarine Canyons form the southern and western margins of a flat shelf which extends from the shore to a depth of 50 fathoms and has a maximum width of three miles. Thus they outline a small area of considerable depth variations which offers an excellent opportunity to study the lateral distribution of grain size and sediment composition.

A collection of 75 samples in the area from the beach, across the shelf, and to the shoreward rim of La Jolla Canyon was made during the summer of 1953. These samples were subsequently analyzed for mineralogic and biologic content and variation of grain size in an attempt to gain a better understanding of the processes of sediment transport and deposition in a neritic environment offshore from a region of rugged topography and relatively great recent changes in shoreline elevation.

Previous Work

Inman (1953), in the only major paper on sediments within La Jolla Bay, described their areal distribution on the triangular shelf bounded by Scripps Canyon, La Jolla Canyon, and the shore (fig. 1). In addition to the study of grain size and composition, Inman related the occurrence of sediments to the complex movement of water resulting from rip currents, longshore currents, and breaking waves near shore. Samples taken at several intervals over the period of one year revealed that most sediments below 30 feet undergo no major seasonal change.

The most authoritative work on the land geology in the vicinity of La Jolla is by Hanna (1926). The Rose Canyon shale and the Torrey and Del Mar sands, which are exposed in 300-foot vertical cliffs at the edge of the sea, constitute important source areas for sediments in La Jolla Bay.

Shepard (1951) investigated the mass movements of sediments at the head of

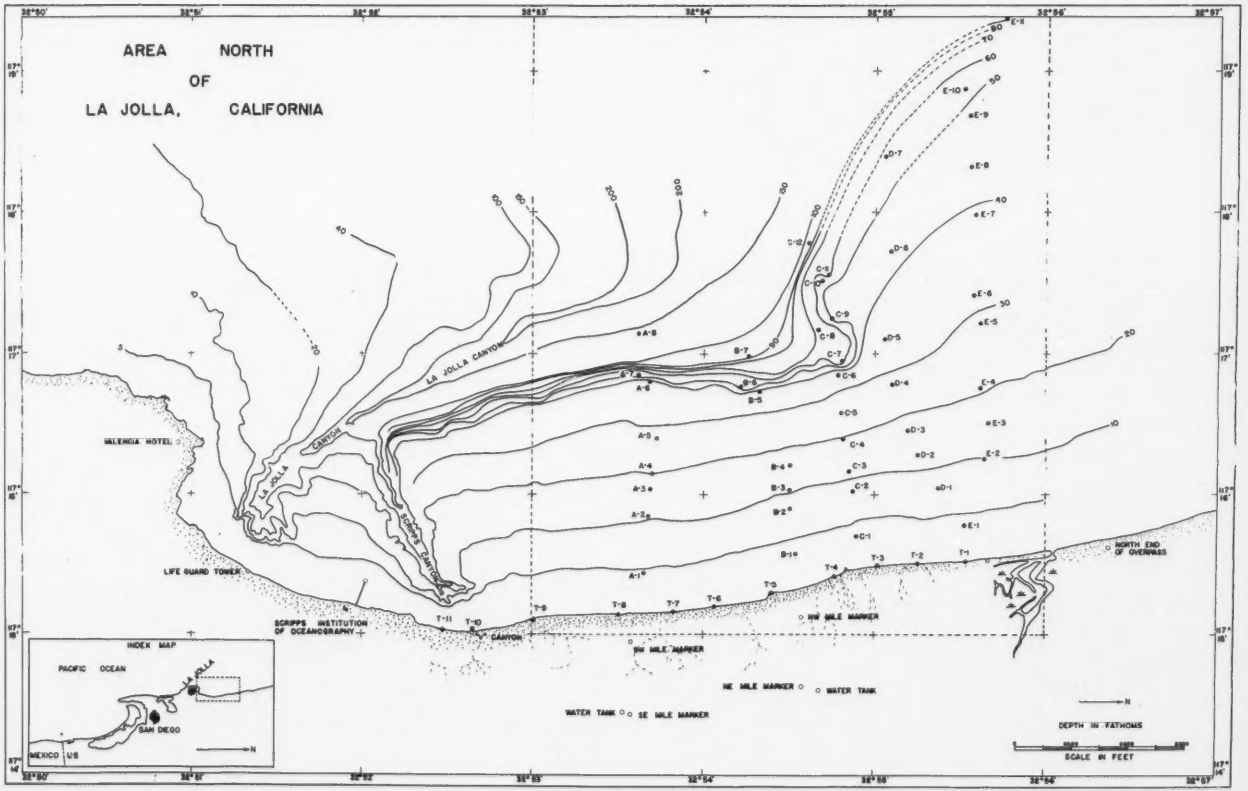


FIG. 1.—Map of the area north of La Jolla, California, showing sampling stations and bottom topography.

Scripps Canyon; and a paper by Shepard and Inman (1950) concerning the relationship between water movement and bottom topography shows that refraction of waves approaching shore over the canyon head results in wave divergence, while at the same time convergence occurs on the adjacent shelf areas. The resulting hydrostatic head causes longshore currents north and south parallel to the shore.

ACKNOWLEDGMENTS

This paper presents the major results of a thesis presented in partial fulfillment of the requirements for the Master of Arts degree in Geology at The University of Texas. Sincere appreciation is expressed to Dr. Robert L. Folk, chairman of the thesis committee, for his excellent guidance and many suggestions for improvement of this paper. The writer is indebted to Dr. Francis P. Shepard of Scripps Institution of Oceanography for the use of ships and laboratory facilities and personal supervision of the summer field work; and to staff members and students at The University of Texas and Scripps Institution. The work would not have been possible without the financial assistance of the Humble Oil & Refining Company Fellowship in Geology.

GEOGRAPHIC SETTING

Submarine Topography

The ocean floor off the coast of southern California consists of numerous basins and ridges which have a northwest trend parallel to the shoreline (Shepard and Emery, 1941) and probably represent fault blocks. Relief in this "continental borderland" ranges from 4000 to 6000 feet and contrasts greatly with the shelf north of Point Conception, where troughs and ridges parallel to the shore are lacking (Revelle and Shepard, 1939). The San Diego Trough, 20 miles offshore and more than 3000 feet deep, trends parallel to the southernmost Pacific shoreline of the United States before extending into Mexican waters. A small tributary of this trench, La Jolla Canyon, stretches eastward in a curving arc toward La Jolla Bay, 12 miles north of San Diego. Within La Jolla Bay the canyon forks and isolates a flat triangular shelf, which was the subject of Inman's sedimentary study. The northern branch is called Scripps Canyon.

Scripps Canyon forms a partial barrier to the passage of southward drifting sand-size particles; that material which falls into the canyon and collects on the floor builds up until it suddenly moves seaward out of the neritic environment, as described by Shepard (1951). Thus the taking of samples in the area just north of Scripps Canyon (the area here investigated) affords the last opportunity to examine the sediments before they are swept out to deep environments except for that material which moves southward around the canyon head.

The featureless bottom in the area of investigation north of the canyon slopes uniformly seaward at the rate of 100 to 150 feet per mile; it probably consists chiefly of submerged Tertiary formations covered by a thin veneer of recent sediments. Rock fragments were found at Station A-7 (fig. 1). Shepard (1949) showed that parts of La Jolla and Scripps Canyons have vertical and even overhanging walls, which are the outcrops of bedrock. Three miles north of Scripps Submarine Canyon, the mouth of subaerial Soledad Valley, a swampy estuary half a mile wide, is almost completely separated from the sea by a sand bar. Once a canyon, this valley has been drowned by the post-glacial rise in sea level. The sediments investigated herein are included in the area from Soledad Valley southward to Scripps Canyon and from the beach westward to the rim of La Jolla Canyon. This area is outlined in figure 1 by dashed lines.

Currents

Most longshore currents off the coast of southern California result from onshore winds blowing obliquely to the

beach. During sampling operations with the *E. W. Scripps* extreme difficulty was experienced in maintaining positions because of rapid southward longshore drift.

Local eddy currents, which are easily observed when one stands on the high bluffs overlooking the northern part of La Jolla Bay, are also important; they are circulating water movements with vertical axes (Shepard and Inman, 1950) related to submarine topography. Because of wave refraction, the waves, converging over the shelf areas adjacent to the canyon heads, result in a hydrostatic head that produces north and south longshore currents. Where such longshore flows meet, they join to form narrow rip currents flowing away from the beach. Certainly these cyclic water movements can cause a more thorough mixing of the sediments on the bottom than if the only water movements were waves and coastal currents.

Land Topography and Geology

Sea cliffs, 300 feet high and nearly vertical in most places, extend along the water's edge the full distance between Soledad Valley and Scripps Canyon. Most of the way a beach 50 to 100 feet wide is present, but in a few places rocky points extend into the water. These cliffs can be considered an important source of sediments because their precipitous faces indicate that erosion by the sea is going on at the present time. The entire coast in this area shows a series of marine terraces, illustrating a history of repeated emergence with intervening stillstands.

The cliffs are capped by the Linda Vista Terrace (Quaternary); in the cliffs Rose Canyon shale and the Torrey and Del Mar sands of Eocene age (Hanna, 1926) crop out. The sands contain clean moderately well-rounded grains of quartz, varying amounts of feldspar, some muscovite and biotite, and minor amounts of ferromagnesian minerals; a few shale beds and oyster reefs occur in the section. The rocks dip regionally southeast, but at a low angle. The Del Mar sand passes under later Eocene beds (Torrey sand) at a point about a mile and a half south of the mouth of Soledad Valley and from there southward forms the lower portion of the sea cliffs. Jurassic granodiorite is exposed 12 to 15 miles inland.

South of the cliffs is Scripps Beach, and beyond it is Point La Jolla, resting on resistant Cretaceous sandstone, which forms vertical cliffs pocketing coarse sand beaches in a few places. The famous La Jolla Caves have been carved in these cliffs by wave action.

METHODS OF COLLECTION AND ANALYSIS

Collection of Samples

The *E. W. Scripps*, a 105-foot schooner especially equipped for marine research, was employed in deep water operations, and a United States Army DUKW was used for the collection of all samples within a mile of shore. Both are equipped with fathometers for continuous depth determinations while underway, and in addition to sample collecting, the *E. W. Scripps* was employed to conduct a fathometer survey on the shoreward rim of La Jolla Canyon. The results of that survey are included in the depth contours of figure 1 within the area enclosed by the dashed lines. Positions for sample collection and the fathometer survey were determined by measuring sextant angles between three known points on shore and by plotting the angles on a chart containing those three points with a three-arm protractor.

Three types of sampling instruments were used. A 150-pound gravity corer with a five-foot core barrel was employed in areas of silt or fine sand; plastic tubes two inches in diameter served as liners to permit quick and efficient removal of the sample so that the corer could be reused immediately. A snapper-type sampler was used in the beginning of the operations, but it frequently failed to close upon contact with the bottom. An orange-peel sampler was the most successful; it al-

TABLE 1.—*Grain size equivalents*

mm	Phi	Grain type	mm	Phi	Grain type
4.00	−2.0		0.125	3.0	
2.83	−1.5	Granules	0.088	3.5	Very fine sand
2.00	−1.0		0.062	4.0	
1.42	−0.5	Very coarse sand	0.044	4.5	Coarse silt
1.00	0.0		0.031	5.0	
0.71	0.5	Coarse sand	0.022	5.5	Medium silt
0.50	1.0		0.016	6.0	Fine silt
0.353	1.5	Medium sand	0.00784	7.0	Very fine silt
0.250	2.0		0.00392	8.0	Coarse clay
0.177	2.5	Fine sand	0.00196	9.0	Medium clay
0.125	3.0		0.00098	10.0	

most always brought up material of sufficient volume to permit study. Its samples were larger than those collected with the corer but by reaching in through the top of the instrument a sample of similar size was easily obtained.

Forty-five sampling stations were established in five ranges extending seaward perpendicular to the shoreline (fig. 1). The sampling interval is one-quarter to one-half mile, and the total area included is six to seven square miles of the Pacific Ocean bottom. In addition, for grain size analysis, eleven sampling stations along the beach were established, and where conditions permitted three samples were taken: (1) at the base of the cliff, (2) on the foreshore about half-way from the berm to the water's edge at low tide, and (3) in the surf zone, approximately four feet deep. Thus a total of seventy-three samples were analyzed.

In sampling operations, one must arbitrarily limit the lateral extent and the vertical thickness of the material to be studied. In this work all samples included, as nearly as possible, only that material which lay within 20 centimeters of the top.

LABORATORY ANALYSIS

The samples were oven-dried, split with a Jones splitter, and one 40-gram portion was set aside for grain size analysis. The beach samples, which are almost entirely sand, were analyzed by the Emery settling tube (Emery, 1938), and the results are essentially comparable with the analyses by sieving (Poole, Butcher, and Fisher, 1951). Twelve beach samples were also sieved. Because the bottom samples contained clay minerals, it was necessary to soak them overnight in a dispersing solution of 0.025 N. sodium hexametaphosphate and then wet-sieve them to separate the coarse fraction (material coarser than 0.062 mm or 4ϕ) from the silt and clay particles. The coarse fraction was dried and sieved on screens with an interval of 0.5 phi ($\frac{1}{2}$ Wentworth grade). Table 1 contains a chart for converting the phi scale (Krumbein, 1938) to millimeters.

Grain size distribution of the silt and clay material (finer than 4 ϕ or 0.062 mm) was determined on six selected samples by the pipette method (Krumbein and Pettijohn, 1938).

The mineralogic and biologic composition of the bottom samples was determined by visual estimation, using the method presently employed by Shepard at Scripps Institution in his study of sediments in the Gulf of Mexico. The percentage by volume of the constituents within each 0.5 phi grade size was estimated; knowing the percentage each one of these grade sizes represented of the total sample, the total percentage of each constituent in the sample was computed. For approximately half of the samples, independent estimates were made by Dr. Shepard and the author and then compared and averaged. Seven categories for

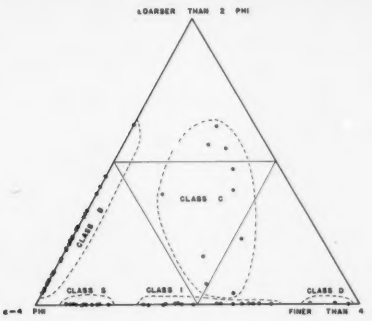


FIG. 2.—Size composition of samples.

estimation were used: (1) light minerals, (2) dark minerals, (3) mica, (4) shell fragments, (5) foraminiferal tests, (6) echinoid shells and spines, and (7) plant fibers. Comparison of separate estimations of the same samples indicate that this estimation method is sufficiently accurate, especially in view of the large sample-to-sample variation.

PROPERTIES OF THE SEDIMENTS

Grain Size Distribution

Size composition.—The sediments in the area of investigation consist mostly of silty very fine sand grading seaward into very fine sandy silt. A triangular plot of all sediments using as the three poles (1) material finer than 4 ϕ (clay and silt), (2) material between 2 and 4 ϕ (fine sand to very fine sand), and (3) material coarser than 2 ϕ (medium sand to granules) divides these samples into five distinct and non-overlapping classes, as illustrated in figure 2. The geographic location of these five classes is outlined in figure 3. The 2 ϕ division was chosen because in most samples this size represents a minimum between two modes in the frequency distribution; the coarse mode occurs only in an isolated area at a considerable distance offshore, the area of Class C in figure 3. Figure 4 illustrates the bimodal frequency distribution (first derivative of the cumulative curve) of material from Station E-8, a typical Class C sediment.

The beach sands (Class B) form a well-defined group (fig. 2) along the side of the triangle representing the absence of clay or silt particles, which have been removed by vigorous expenditure of wave energy in the littoral zone.

Sediments from the shallow and intermediate depths on the shelf form two separate classes (Class S and Class I) extending along the side representing the absence of coarse particles (coarser than 2 ϕ), the mud content increasing almost linearly with depth. Some mud is present in each sample because of the reduced wave energy in deeper water, and mud that is washed from the cliffs and canyons must settle where the water motion is less pronounced than at or near the beaches.

Deep-water sediments from the steep canyon sides form a third group (Class D), inasmuch as they consist very largely of silt with some clay and very little sand.

Class C (composed of samples containing more than three percent coarse

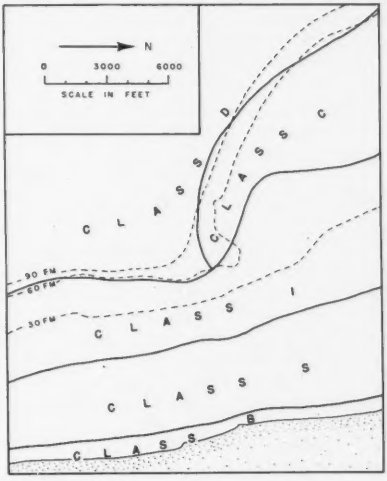


FIG. 3.—Location of the sediment classes.

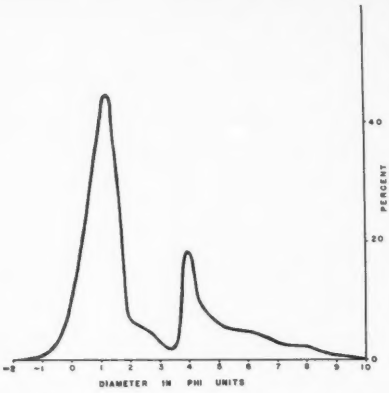


FIG. 4.—Frequency distribution of grain diameter, sample no. E-8. This is a typical Class C sediment.

particles, exclusive of beach sands) comprises ten samples scattered throughout the center of the triangular diagram. Occurring at depths of 40 to 60 fathoms along Ranges D and E, these samples are quite anomalous in that they usually contain a bimodal mixture of clayey silt, coarse sand, very coarse sand, and granules. The cumulative curves of these samples appear to indicate that silt and clay, the "normal" sediment of other samples in this depth range, have been superimposed upon a curve of coarse material. Figure 5 is a contour map of particles coarser than 2 ϕ and illustrates that Class C sediments occur in a compact group in the northwest portion of the area of investigation, separated from the present shoreline by a two mile strip in which virtually no coarse material is present. This intervening strip indicates that the coarse particles probably were not carried there by ordinary shoreline processes, and that the coarser material farther from shore may therefore be the product of surf action during a time of lowered sea level, perhaps during a glacial maximum. As the sea level rose to its present height, drowning Soledad Valley, the old beach sediments of the outer shelf were mixed with silt and clay, producing the bimodal curve found in that area today.

Median grain diameter.—Median grain diameter varies from 1.4 ϕ (0.379 mm, medium sand) in the Class C group to 5.2 ϕ (0.027 mm, medium silt) on the canyon rim. The decrease in diameter from the surf zone outward (except for Class C) is correlative with the increase in depth according to the least squares equation

$$Md\phi = 0.0208D + 3.30$$

where $Md\phi$ represents the median diameter in phi units and D represents the depth of water in fathoms. This strikingly linear relationship, with a correlation coefficient of +0.95 holds true to depths of 120 fathoms. The only exception is in the northwest portion of the area where the median diameters of the Class C sediments increase erratically. Cumulative curves of those samples are

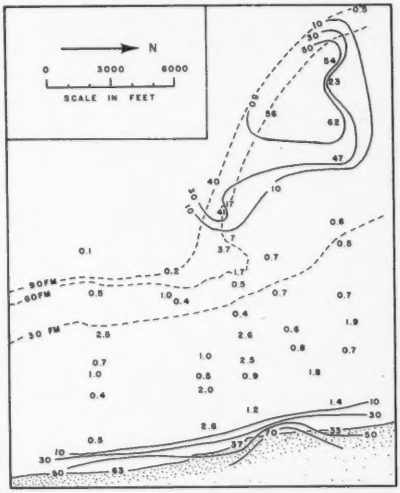


FIG. 5.—Distribution of coarse particles. Values in percent by weight of the total sample.

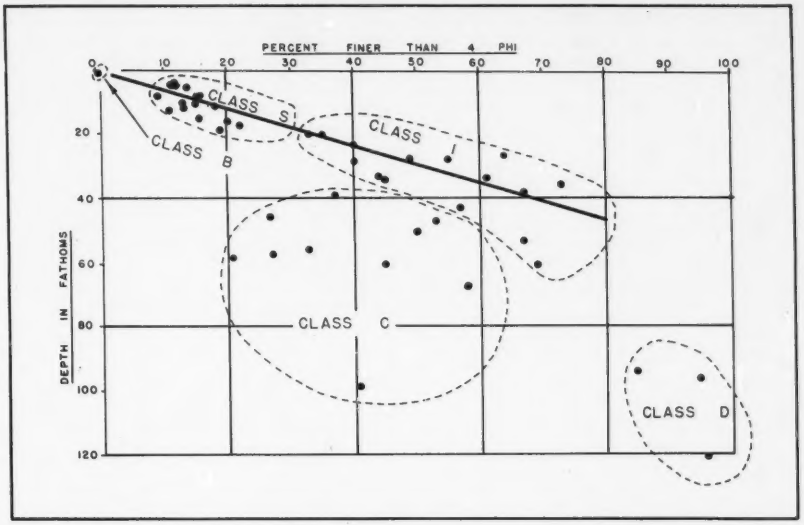


FIG. 6—Mud-depth relationship. The equation for the line is: Mud = 1.74 (Depth in Fathoms) − 1.93.

nearly flat in the 40 to 60 percent range because of their strongly bimodal character, and thus their median diameter values are unreliable.

Mud Content.—The term "mud" is used throughout this paper to include all particles finer than 4 ϕ —i.e., silt and clay particles. A diagram of percent of mud versus depth in fathoms (fig. 6), shows a remarkably linear trend for all samples except those of Class C, which scatter randomly throughout the diagram. The samples shallower than forty fathoms yield a correlation coefficient of depth with mud content of +0.92, and the relation can be represented by the least squares equation

$$M = 1.74D - 1.93$$

where M is the percent of mud and D is the depth in fathoms. The high correlation coefficient means that among all of the factors which determine mud content, the water depth is responsible for

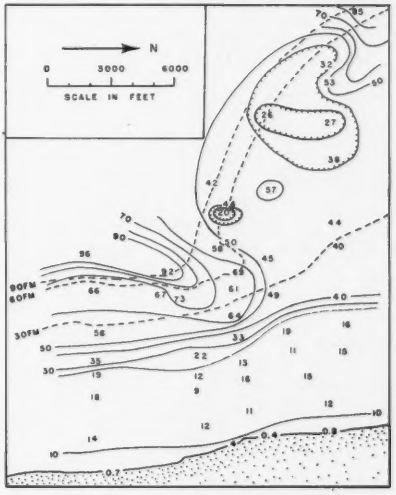


FIG. 7.—Mud content. Values in percent by weight of the total sample.

most of the variation. This adds supporting evidence to the generalized textbook statement that mud content increases with depth where wave action is dominant. Figure 7, a contour diagram of percent of mud, illustrates a small percent terrace —i.e., the mud content remains essentially constant at about 15 percent for a distance of some 4000 feet offshore and then suddenly increases to about 35 percent at twenty fathoms, without any noticeable change in topography. Perhaps this is a result of the eddy motion of water near shore (Shepard and Inman, 1950), since it seems likely that the outgoing rip currents would cause a more thorough mixing of sediments near shore than would occur in the absence of such currents. Samples with less than 25 percent silt and clay fall into Class S of the triangular diagram (fig. 2) and those with 33 to 73 percent silt and clay fall into Class I.

The mud fraction (material finer than 4 ϕ) of most of the sediments consists chiefly of silt-size igneous and metamorphic rock minerals. In the shallow water samples, the 4.0 to 5.0 phi interval is mostly heavy minerals, while in sediments from deepest waters, containing less than five percent sand, the fine fractions are three-quarters silt-size grains and one-quarter clay-size grains. Clay minerals themselves (mostly illite) form only a very small amount of the sediment, as indicated by X-ray analyses. The lack of clay minerals probably results from the relatively arid climate which retards the chemical decay of feldspars and from the relatively rugged

TABLE 2.—*Classification of sediments*

Class	Samples			Depth	Silt+clay	Particles coarser than 2 ϕ
S (shallow)	A-1	B-1	C-1	4–18 fms	0–25%	0–3%
	A-2	B-2	C-2			
	A-3	B-3	C-3			
		B-4				
	D-1		E-1			
	D-2		E-2			
	D-3		E-3			
I (intermediate)	A-4	B-5	C-4	19–61 fms	33–73%	0–3%
	A-5	B-6	C-5			
	A-6		C-6			
			C-7			
	D-4		E-4			
	D-5		E-5			
	D-6		E-6			
D (deep)	A-8	B-7	E-11	93–120 fms	85–96%	0–3%
B (beach)	T-1	T-4	T-9	Beach and surf zone	0–5%	4–65%
	T-2	T-6	T-10			
	T-3	T-7	T-11			
		T-8				
C (coarse particles)	C-8	D-7	E-7	39–98 fms	21–58%	3–62%
	C-9		E-8			
	C-10		E-9			
	C-11		E-10			
	C-12					

TABLE 3.—*Mineral composition*

Sample	Interval	Quartz	Orthoclase + Microcline	Plagioclase	Mica	Heavy Minerals
A-1	3–4 ϕ	28	10	1	0	11
B-4	3–4 ϕ	25	13	2	6	4
C-7	3–4 ϕ	30	8	1	5	7
D-6	3–4 ϕ	34	8	2	0	6
E-8	3–4 ϕ	28	7	5	4	7
F-8	1–2 ϕ	36	13	1	0	0
T-7b	3–4 ϕ	15	5	1	0	29
T-7b	1–2 ϕ	36	8	5	0	1

topography of the California coast.

Classification summary.—A natural grouping of sediment types, which on the basis of these samples occupy distinct, non-overlapping geographic units, exists for the area north of Scripps Canyon (Table 2). The unusually coarse bimodal nature of Class C sediments suggests the superposition of present sedimentation conditions upon a former area of coarse material, such as might have been formed along a beach during time of lower sea level.

Mineralogic and Biologic Content

Of the seven major constituents in the coarse fractions of these samples, three (light minerals, dark minerals, and mica) have areal distributions highly significant of their hydraulic properties. Four of the constituents (shell fragments, foraminiferal tests, echinoid shells and spines, and plant fibers) constitute a higher percentage of the coarse fractions in deeper water samples. Since the coarse fractions become smaller in deeper waters, this may merely represent a uniform distribution of organic material throughout the entire area. In addition to the above constituents, ostracods, radiolarians, diatoms, and fish teeth occur in some of the samples.

Light minerals.—The light mineral group includes all the light-colored terrigenous minerals, which are chiefly subangular quartz and feldspar. It also includes a few shale fragments and worm pellets composed of tiny particles of all types, but both of these are essentially light-weight material. The range of light minerals is between 72 and 97 percent of the coarse fractions, the largest percentage occurring on the beach and in the area of Class C sediments. In the latter are found coarse quartz and feldspar sands and abraded but subangular granules of vein quartz and fine-grained quartzose schist, which may be the remains of the old beach, now under 40 fathoms of water.

A count of minerals in seven selected samples (table 3) revealed that the ratio of quartz to feldspar grains is approximately two or three to one, indicating that sediments in this area constitute a marine arkose resulting from violent tectonic activity, a conclusion corroborated by the earthquakes and elevated marine terraces.

Dark minerals.—The dark mineral group includes all dark-colored particles excepting mica, plant fibers, and gray rock fragments, all of which would act hydraulically as light-weight material. The dark minerals consist chiefly of dark greenish hornblende and minor amounts of glaucophane, epidote, garnet, and apatite; thus they give a good indication, except for zircon, of the heavy mineral content. The range is between zero and 18 percent of the coarse fractions of the bottom samples, with greatest abundance near water of five to 15 fathoms (fig. 8); here, too, the fine fractions (which are mostly silt) consist chiefly of heavy minerals, and as a result the heavy

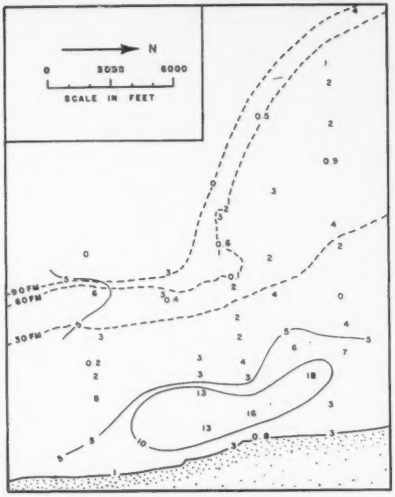


FIG. 8.—Distribution of dark minerals. Values in percent of the coarse fraction.

mineral content is greater than shown on the map. The maximum of heavy minerals just seaward of the surf zone results from the inability of water to transport them farther.

Mica.—The mica group, which includes fresh biotite and a little muscovite, averages six to seven percent of the sediments, the greatest concentrations occurring in intermediate depths (fig. 9). The plate-like mineral is carried away by currents too weak to transport nearly spherical grains of the same size. Thus any mica near shore is picked up by wave action and remains in transport until the water movement becomes too weak to suspend it; it is deposited farther from shore with quartz of much smaller size.

Shell Fragments.—Gastropod, scaphopod, and pelecypod shell fragments, most of which were broken on arrival at the surface and others unavoidably crushed during the subsequent laboratory processing, constitute between 0.01 and 18 percent of the fractions larger than 4.0 phi. The greatest abundance within the coarse fractions occurs near the rim of La Jolla Canyon. If the shell material were of uniform concentration throughout the area, a seaward decrease in total coarse fraction material would produce a corresponding increase in shell material by default, resulting in the distribution actually found in this area.

Foraminiferal tests.—Foraminifera, both whole and fragmental, show a correlation with depth similar to the other shell materials—i.e., within the coarse fraction they have greater abundance in deeper water. The range is between zero and seven percent, but since the coarse fraction decreases outward, a uniform distribution of foraminifera would show a corresponding increase, as its does here.

Echinoid shells and spines.—The class that includes both spines and echinoid shell fragments, which have an easily recognizable "sugary" appearance, constitutes less than three percent of any sample. Investigations at Scripps Institution have found these shells indicative of cer-

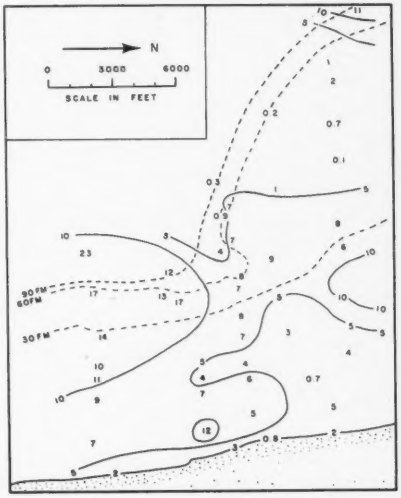


FIG. 9.—Distribution of mica. Values in percent of the coarse fraction.

tain environments, but in La Jolla Bay they are scattered throughout with no apparent correlations.

Plant fibers.—The plant fiber group, including fragmental leaves and stems of marine plants, shows no correlation with depth in the area investigated. No sample contains more than two percent plant fibers, and most of them contain less than 0.5 percent in the coarse fractions.

INDICATIONS OF A BURIED SUBMARINE CANYON

The origin of submarine canyons has been a field of much study and speculation in recent years. It seems doubtful that a single explanation of origin will ever fit all canyons; it is more probable that continued study will again and again demonstrate that these phenomena must be analyzed individually.

In addition to genesis, the student of submarine topography must explain why nearshore submarine canyons are not quickly filled with sediments, as the tendency of marine erosion and deposition is to smooth out an irregular bottom. Coastlines may contain hundreds of submarine canyons that join with subaerial canyons to reflect ancient drainage, but, if the submarine portions of these valleys have been filled with neritic sediments since submergence, only geophysical surveys will dislcose them. Origin of the unfilled canyons is no greater mystery than their preservation.

La Jolla Canyon is the continuation of a broad valley, two miles long and half a mile wide, which cuts through the terrace overlooking the sea. Scripps Canyon is the submarine continuation of a small, steep canyon, less than a third of a mile long and cutting through 300 feet of sandstone and shale. This evidence points strongly toward a subaerial erosional origin, but does not explain the factors involved in keeping the canyons cleared of sediment today. Farther north, Soledad Valley is an even more prominent topographic feature, yet no apparent present-day submarine canyon connects it with the ocean depths. In an early discussion of California submarine canyons, William Morris Davis (1934) stated that

> "... ordinary depositional processes, which have unquestionably been acting to build up the shallower sea floor adjoining the submarine valleys, ought to have obliterated the inner parts at least of the existing submarine valleys, unless some marine process of opposite nature and still in operation had kept them empty."

Examination of the depth contours of figure 1 reveals that not only does the broad estuary just north of Station T-1 make one suspect a submarine continuation similar to La Jolla Canyon, but the small submarine valley near Stations C-6, C-7, and C-8 suggests its point of junction with La Jolla Canyon. Perhaps the processes which maintain and preserve Scripps and La Jolla Canyons to the south near Point La Jolla do not prevail farther north, where former canyons may have been filled and disappeared. One such buried canyon would form the missing link between Soledad Valley and La Jolla Canyon, uniting all of the canyons, subaerial and submarine, with the San Diego Trough in a single drainage pattern.

CONCLUSION

The two diagrammatic profiles in figure 10 represent the more important results of the investigation in this area. Each of these generalized sections, parallel to the ranges, represents typically the variations in grain size and mineral composition from east to west. Range D-E, on the north, stretches across a shelf width nearly twice as great as that of Range A-B, on the south where La Jolla Canyon approaches nearer to the present shoreline. An unusual increase in coarse particles (coarser than 2 ϕ) occurs in the northern range two to three miles from the beach, whereas the samples from the intervening area contain no such particles; it is concluded that the coarse particles are probably not being

derived from present-day erosion of the coast; rather these abraded grains may represent the former beach of a lower sea level. If so, the oceans must have overlapped the shelf approximately one mile, drowning La Jolla Canyon to the present-day 40-fathom contour. The coarse particles are absent from the two southern ranges (A and B), possibly because the steep canyon walls permitted fragments to fall to the floor of the canyon.

Except in this anomalously coarse area, the sediments show a strikingly linear increase of mud content (actually largely silt) with depth, represented by the following equation:

Mud percentage = 1.74 (Depth in fathoms)—1.93

The sudden drop in mud content about a mile offshore (probably caused by rip currents) is plainly reflected in both profiles of figure 10; dark minerals occur in highest percentage shoreward of this percent scarp, whereas mica is concentrated on the seaward side of this feature. As there is no topographic break along this line, these facts illustrate the different hydraulic properties of mica and the dark minerals.

There are three possible sources for the sediment: (1) the high sandstone and shale cliffs that face the Pacific Ocean, (2) the igneous area in the interior, which is drained through Soledad Valley, and (3) that portion of the coast north of La Jolla Bay from which sediments may be carried southward by coastal currents.

Most probable source areas for these sediments are the 300-foot cliffs immediately behind the beach, for the mechanical analyses indicate continuous decrease in grain size outward from shore, but not southward parallel to the beach. In addition the precipitous cliffs are due to active wave action at the base. Steep gullies in these cliffs may also yield important quantities of sediments during rains. In subsequent studies of this area, samples from these cliffs should be compared with samples of bottom sediments; similarities and differences in roundness, grain size, mineral types, and other characteristics might lead to the discovery of the source of these sediments. There can be little doubt, however, that this area of investigation represents the last nearshore position before the sediments are carried to deeper waters via La Jolla and Scripps Canyons.

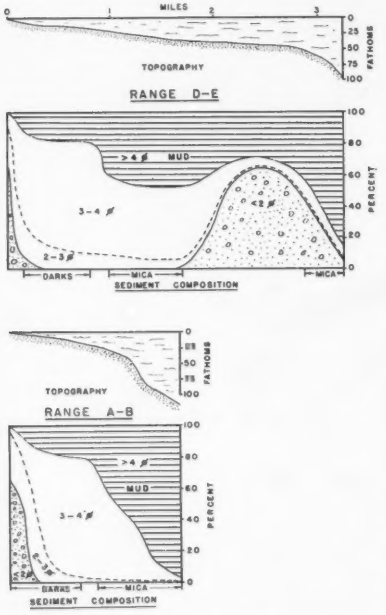


FIG. 10.—Diagrammatic profiles. Profile of Range A-B is a composite section representing the composition of Range A and Range B. Range D-E represents Range D and Range E.

REFERENCES

DAVIS, W. M., 1934, Submarine mock valleys: Geog. Rev., v. 24, pp. 297–308.

EMERY, K. O., 1938, Rapid method of mechanical analysis of sands: Jour. Sedimentary Petrology, v. 8, pp. 105–111.

HANNA, M. A., 1926, Geology of the La Jolla quadrangle, California: Univ. of Calif. Publications, Bull. Dept. Geological Sciences, v. 16, pp. 187–246.

INMAN, D. L., 1953, Areal and seasonal variations in beach and nearshore sediments at La Jolla, California: Beach Erosion Board, Technical Memorandum 39.

KRUMBEIN, W. C., 1938, Size frequency distributions of sediments and the normal phi curve: Jour. Sedimentary Petrology, v. 8, pp. 84–90.

KRUMBEIN, W. C. and PETTIJOHN, F. J., 1938, Manual of sedimentary petrography. D. Appleton-Century, New York, 549 pp.

POOLE, D. M., BUTCHER, W. S., and FISHER, R. L., 1951, The use and accuracy of the Emery settling tube for sand analysis: Beach Erosion Board, Technical Memorandum 23.

REVELLE, R. and SHEPARD, F. P., 1939, Sediments off the California coast: in Trask, P. D. (editor) Recent Marine Sediments: a symposium, Am. Assoc. Petroleum Geologists, pp. 245–282.

SHEPARD, F. P., 1949, Terrestrial topography in submarine canyon heads revealed by diving: Geol. Soc. America Bull., v. 60, pp. 1597–1612.

———, 1951, Mass movements in submarine canyon heads: Trans. Amer. Geophysical Union, v. 32, pp. 405–418.

SHEPARD, F. P. and EMERY, K. O., 1941, Submarine topography off the California coast: Geol. Soc. America, Special Paper 31.

SHEPARD, F. P. and INMAN, D. L., 1950, Nearshore water circulation related to bottom topography and wave refraction: Trans. Amer. Geophysical Union, v. 31, pp. 196–212.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 38–40
FIGS. 1–3, MARCH, 1955

TWO UNUSUAL OCCURRENCES OF MICROSTYLOLITES

BENJAMIN H. BURMA AND CHARLES M. RILEY
University of Nebraska, Lincoln, Nebraska

ABSTRACT

Microstylolites are here reported in both quartzite and in welded tuff. Descriptions of these unusual occurrences and accompanying photomicrographs suggest difficulties in applying the widely held theory of pressure—solution for the origin of these features.

INTRODUCTION

The purpose of this paper is to place on record two unusual occurrences of microstylolites. One example concerns microstylolites in quartzite, discovered by Burma; the other in what is apparently a welded tuff, discovered by Riley.

There are few records of stylolites in quartzite in the literature. Conybeare described microstylolites from an early Proterozoic quartzite (Conybeare, 1949) and casually mentioned another such occurrence (Conybeare, 1950). Tarr (1916) described macrostylolites from Dakota quartzite in Colorado. Price described problematical macrostylolites in Medina quartzite (Price, 1934).

Stylolites in quartzitic sandstone have a slightly more extensive record in the literature. Andrews (1947), Price (1934) and Stockdale (1936, 1945) have described macrostylolites in quartzitic Pennsylvanian (Pottsville) sandstone along the Appalachian area from Maryland to Alabama. Sloss and Feray (1948) similarly described microstylolites in a Cretaceous quartzitic sandstone in Montana.

All the above authors attribute the stylolites in sandstones and quartzites to pressure-solution. Shaub (1947, 1950) has disputed this origin, but his alternative theory seems even less capable of accounting for the phenomena described.

MICROSTYLOLITES IN THE SIOUX QUARTZITE

The microstylolites in quartzite observed by us were found in a glacial cobble found in the vicinity of Lincoln, Nebraska. It rather obviously came from the outcrop area in eastern South Dakota—southwestern Minnesota. The Sioux quartzite of this area is virtually undisturbed, and apparently has never been subjected to an orogeny, in contradistinction to the quartzites and sandstones mentioned above. This is substantiated by the unstrained, uncrushed, unsheared nature of the quartzite specimen in hand.

The quartzite itself is composed of a poorly sorted mixture of coarse sand to silt. The subangular nature of the grains and the low degree of sorting suggest that the original sandstone would have had a low porosity. The small amount of original pore space has in the main been filled with mosaic quartz. (figs. 1, 2)

The quartzite shows a rude graded bedding, and the microstylolites are apparently concentrated at the lamella boundaries, although not entirely restricted to them. They usually make their way between the grains, many of which show beautifully sutured boundaries, but occasionally cut across a grain or across an area of quartz cement. For these reasons, there seems to be no doubt that the stylolites formed after the quartzite

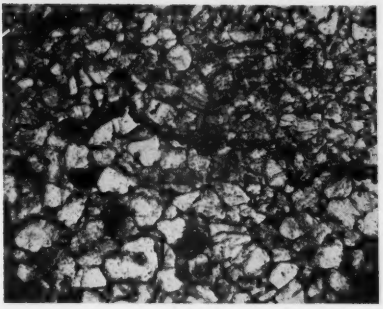


FIG. 1.—Microstylolites in Sioux quartzite. ×30.

was cemented into a rock which was virtually free of voids.

The situation is peculiar. Here are well developed microstylolites in a highly insoluble rock which could have had little or no circulating water in it. The petrographic study yields little evidence of particularly deep burial, or metamorphism of consequence, and no evidence of orogeny is reported for this area of the Sioux outcrops. In these circumstances, the pressure-solution theory seems difficult to apply, but we can suggest nothing better.

MICROSTYLOLITES IN WELDED TUFF

No references have been found in the literature to stylolites in tuffs. It thus is doubly unfortunate that no locality data can be given for our specimen. It was part of a collection purchased many years ago and on which no data remain. The character of the material suggests that it is of middle or late Tertiary age and is from the western United States. The rock itself is a tuff and almost certainly a welded tuff. Pore space is approximately nil. The rock is a dark-red aphanite, of procelainous luster, containing numerous light colored small "phenocrysts." In thin-section, (fig. 3) shard-phantoms are quite evident as is a strongly developed layering displaying minute compaction structures. Mineralogically, the rock carries albite, orthoclase, quartz, and biotite and abundant devitrified glass, with secondary sericite, chlorite, hematite, and leucoxene.

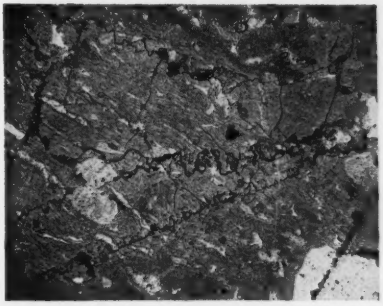


FIG. 3.—Microstylolites in welded tuff. ×30.

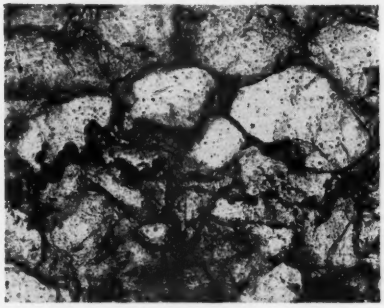


FIG. 2.—Microstylolites in Sioux sandstone. ×80.

A most striking feature is the extremely well developed microstylolites which cut indifferently across all the minerals. They appear to occur in three inclined sets, one approximately parallel to the layered structure. The suture is characteristically lined with chlorite, or less commonly sericite. Here again there is the difficulty of accounting for a supposed solution feature in a well-nigh impervious rock. The occurrence of the stylolites in three sets is also a complication and suggests that static load is not re-

sponsible. The chlorite in the sutures suggests some hydrothermal action, but although all the feldspars are somewhat sericitized, the extent of it is hardly more than one would expect as a result of the self alteration by hot gases in a cooling ash-bed. No satisfactory explanation presents itself.

REFERENCES

ANDREWS, D. A., 1947, Significance of stylolites in sandstone (Abst.): Washington Acad. Sci. Jour., v. 37, pp. 372–373.

CONYBEARE, C. E. B., 1949, Stylolites in pre-Cambrian quartzite: Jour. Geology, v. 57, pp. 83–85.

———, 1950, Stylolites in pre-Cambrian quartzite: a reply: Jour. Geology, v. 58, pp. 652–654.

PRICE, P. H., 1934, Stylolites in sandstone: Jour. Geology, v. 42, pp. 188–192.

SHAUB, B. M., 1947, Coal partings in stylolite seams: Jour. Sedimentary Petrology, v. 17, pp. 114–118.

———, 1950, Stylolites in pre-Cambrian quartzite: Discussion: Jour. Geology, v. 58, pp. 650–652.

SLOSS, D. D. and FERAY, D. E., 1948, Microstylolites in sandstone: Jour. Sedimentary Petrology, v. 18, pp. 3–13.

STOCKDALE, P. B., 1936, Rare stylolites: Am. Jour. Sci., 5th ser., v. 32, pp. 129–133.

———, 1945, Stylolites with films of coal: Jour. Geology, v. 53, pp. 133–136.

TARR, W. A., 1916, Stylolites in quartzite: Science, new ser., v. 43, pp. 819–820.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 41–44
PL. 1, MARCH, 1955

SAND PIPE FROM THE SEA FLOOR OFF CALIFORNIA

HIROSHI NIINO
Tokyo University of Fisheries, Tokyo, Japan[1]

ABSTRACT

A sand pipe dredged from the sea floor off California is believed to have formed as a crab or worm burrow in Miocene sediments. Its shape is similar to other sand pipes dredged off Japan.

INTRODUCTION

This paper describes a sand pipe which has been preserved for about 15 years in the museum of the Scripps Institution of Oceanography at La Jolla, California. It is the largest and most perfectly preserved of several dredged in 1938 from the east wall of the Point Dume submarine canyon at Latitude 33°58.6′ N., Longitude 118°48′ W., 420 meters deep. The dredging was done form the research vessel *E. W. Scripps* of the Scripps Institution by F. P. Shepard, K. O. Emery, and R. S. Dietz.

This is the only known case of sea floor sand pipe found along California, but similar pipes have commonly been dredged off Japan (Niino, 1933, 1952). The author has recovered them from 14 stations at depths between 74 and 604 meters. The Japanese sand pipes are variable in shape, some being straight and others branching, but almost all display a straight cavity. They are composed of hard calcareous sandstone which contains many kinds of fossils such as mollusks, foraminifera, portions of crabs, etc. The fossils and sand grains are randomly oriented and are cemented by calcite, aragonite, or clayey materials.

Sedimentary rocks usually accompanied the Japanese sand pipes; thus, it is likely that the pipes have been eroded from these rocks so that they are fossil rather than recent. Seventh-five pieces of concretionary limestone of Miocene (?) age were dredged with the sand pipes at the Dume Canyon locality (Emery and Shepard, 1945) so the fossil nature of the sand pipe described here is also likely.

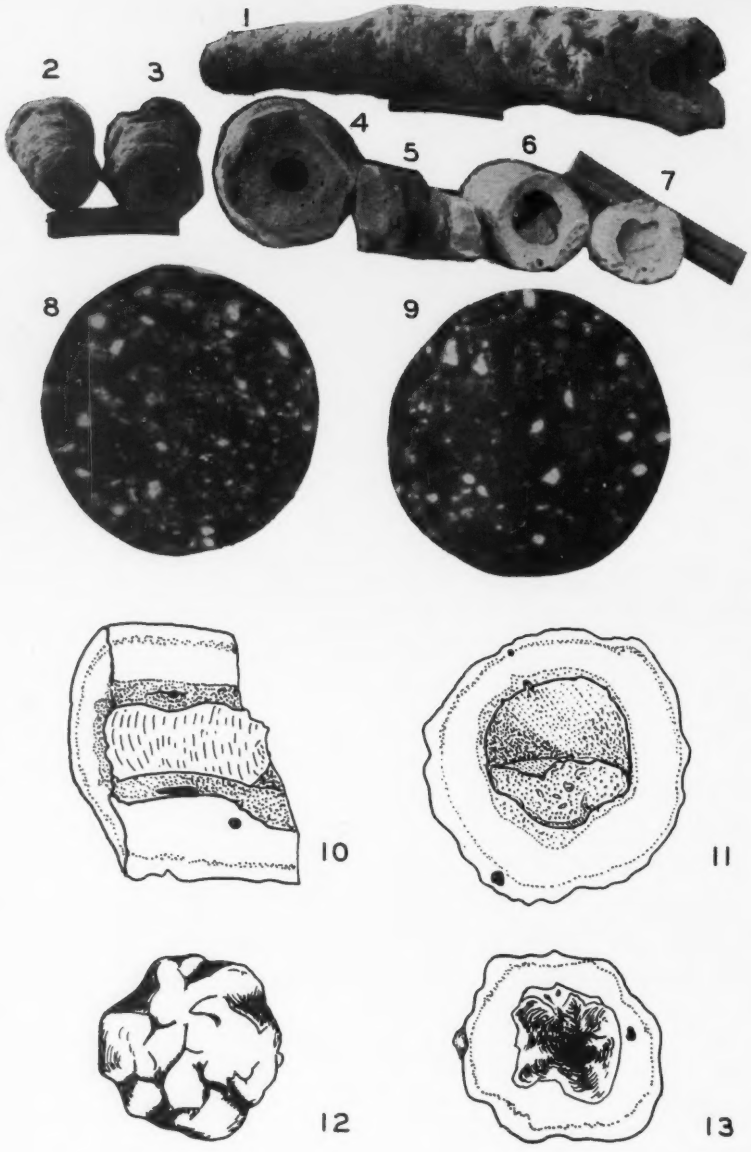
The fragments of fossil crabs and worm mandibles that commonly are associated with Japanese sand pipes suggest that the pipes originated as crab or worm burrows formed at the time that the sedimentary rock was deposited. The similar appearance and construction of the pipe described here suggest the same origin although few identifiable crab or worm fossils were found.

DESCRIPTION OF THE SAND PIPE

The sand pipe is almost straight, 72 cm long, 11 cm in diameter at the open front end and tapers to six cm at the closed rear. In the center along the axis there is a cavity which is open in front and closed at the rear. The diameter of this cavity is 7.5 cm at the front but it abruptly becomes narrower at a distance of about 20 cm from the opening; from this point to the closed end the diameter of the cavity is about four cm. The wall thickness of the pipe is 4.5 cm at the opening and 3.5 cm from the middle to the end but the terminate wall is only one cm thick. The end of the cavity is partially blocked by a recent fill of sandy clay.

The inner surface of the cavity is very smooth except at the front opening and at the terminal end. Near the opening, the surface of the cavity is rough and many organisms are attached. At the in-

[1] Visiting Research Associate, Scripps Institution of Oceanography, La Jolla, California.


1
2
3
4
5
6
7
8
9
10
11
12
13

ner surface of the closed end there is a peculiar kind of relief that is characteristic of the terminal configuration of a crab hole.

The outer surface of the sand pipe is rough and shows an alternation of ridges and grooves which are arranged obliquely to the axis. It seems that their relief might have originated by the varied hardness of layers of strata in which the sand pipe was formed. Many small grooves and holes made later by boring organisms also can be observed on the surface of the sand pipe. Recent organisms attached to the surface of the sand pipe include bryozoans, barnacles, corals, and worm tubes. It is evident that the pattern of attached organisms is not uniform but one side has more than the other side. It appears likely that the sand pipe may have been rolled on the bottom but that the side with the most organisms and holes was usually uppermost.

STRUCTURE OF THE SAND PIPE

The sand pipe is made of calcareous sandstone which contains fossils with no systematic arrangement in the rock. They include a pelecypod (*Yoldia sp.* indet.), a gastropod (*Certhium sp.* indet.), two kinds of foraminifera (*Robulus sp.*, *Quinqueloculina sp.*), and some poorly preserved fragments of crabs.

The wall of the pipe consists of three differently colored layers. Around the internal cavity is a thin layer of yellowish soft sandstone, about one cm thick. This layer is easily distinguished from the main layer by its softness and color. Along the circular boundary between inner layer and main layer are several holes made by organisms. These holes begin their opening at the inner surface of the cavity and are drilled through the soft layer but at the contact with the hard main layer they turn and follow the boundary.

The main layer, when observed with a microscope, is seen to have a predominance of quartz and biotite grains which are arranged perpendicularly to the axis of the sand pipe. Some tests of foraminifera are present. At a depth of three to eight mm from the outside of the main layer is a black zone having a thickness that varies between one and three mm. Small grains of concretionary limonite can be observed, but it is uncertain that the color of this zone originates from this mineral. The appearance is closely allied to the "liesegang rings" which are common in homogeneous sedimentary rock; therefore, it is possible that the black zone was formed in the sand pipe during the time when it was resting loosely on the sea floor or during the time that it has been kept in the museum.

Outside of the main layer is a thin layer of whitish-gray sandstone which forms the surface of the sand pipe. It is weathered and pitted by boring organisms.

LEGEND FOR PLATE 1

1. Appearance of the sand pipe. The scale on the pipe is 15 cm long.
2. Terminal outside of the sand pipe.
3. Cross-section at 45 cm from the opening.
4. Section next to number 3.
5. Longitudinal section at 45 cm from the opening.
6. Cross-section at six cm from the terminal. Two-thirds of the area of the inner cavity is filled by clayey mud.
7. Inner view of the terminal cavity.
8. Photomicrograph of a thin-section of the sand pipe (transversal section, ×32).
9. Photomicrograph of longitudinal section (×32).
10. Longitudinal section of the sand pipe showing black spotted zone and inner soft yellowish layer. Large black spots are the holes of boring organisms.
11. Cross-section at six cm from the terminal. Sandy clay fills part of the cavity.
12. Appearance of the outer surface of the terminal.
13. Characteristic striae in the inside of the terminal of the cavity.

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to Robert S. Dietz who suggested the study of the sand pipe and also to Francis P. Shepard who kindly provided facilities for this study. Dietz and K. O. Emery read and corrected the manuscript.

REFERENCES

NIINO, HIROSHI, 1933, On the sand pipe dredged from the sea bottom around the Japanese Islands: Jour. Geographic Association of Tokyo, v. 45, [no. 528], pp. 1–6.

NIINO, HIROSHI, 1952, The bottom character of the banks and submarine valleys on and around the continental shelf around the Japanese Islands: Jour. Tokyo University of Fisheries, v. 38, [no. 1] pp. 353–410.

EMERY, K. O. and SHEPARD, F. P., 1945, Lithology of the sea floor off southern California: Bull. Geol. Soc. America, v. 54, pp. 431–478.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 45–50
MARCH, 1955

CLASSIFICATION OF PERMIAN ROCKS OF WESTERN TEXAS BY A VERSENATE METHOD OF CHEMICAL ANALYSIS[1]

RICHARD G. GUERRERO AND CHARLES T. KENNER
Southern Methodist University, Dallas, Texas

ABSTRACT

There is much confusion regarding the classification of the more common carbonate rocks of the limestone-dolomite series and the combinations of these with silt or clay. A modification of Pettijohn's quantitative scheme is applied to Permian rock samples[2] by the use of a versenate method of chemical analysis. In the Permian rocks of the Malone Mountains, the Black Brecciated limestone is actually a dolomite and the Buff limestone a mixture of calcitic dolomite, dolomite, and dolomitic limestone. Likewise, some of the rocks in the Permian system of the Finlay Mountains that have been called "limestones" are in reality dolomitic limestone, while certain "shales" are consolidated dolomitic limestone marls.

INTRODUCTION

There is much confusion regarding the classification of carbonate rocks. Pettijohn (1948), Shrock (1948), Krynine (1948), and Rodgers (1950) all agreed that the existing suggested classifications are unsatisfactory. Later, Shrock (1948) proposed a classification based primarily on the mode of formation of the particles or crystals and, secondarily, on descriptive characteristics, but without any name for the gradational rocks in the limestone-dolomite series. Grabau (1904) proposed a genetic classification which, according to Pettijohn (1949), has not found favor mainly because of the considerable number of unfamiliar rock names. Also, in most cases, it is desirable to name a rock before undertaking the problem of its origin. Krynine's (1948) descriptive classification fails to cover rocks that are mixtures of clay, calcite, and dolomite, and, therefore, falls short of a comprehensive system for carbonate rocks.

Van Tuyl, (1914), in his extensive study on the origin of dolomite, states that the attempted classifications of limestone and dolomite show much uncertainty and lack of regard of the importance of the magnesia content in the rock.

Of all the proposed systems of classification, Pettijohn's (1949) chemical scheme seems to be the only one which allows an accurate classification of the intergradations of the carbonate rocks. In this report, a modification of Pettijohn's quantitative scheme is proposed and is applied to Permian rock samples by the use of a versenate method of chemical analysis.

PROPOSED CLASSIFICATION CHART

The bottom line of the chart is made of divisions obtained by converting the limestone-dolomite percentages of the calcite-dolomite mixtures from Pettijohn's (1949) classification into a mole ratio of the calcium oxide to the magnesium oxide. Pettijohn's percentages based on 100 percent carbonate material are no longer used, for the mole ratio line represents the total carbonate fraction whether it makes up 100 percent of the sample or less. If there is insoluble resi-

[1] Condensed from the thesis submitted by Richard G. Guerrero to the Graduate School of Southern Methodist University in partial fulfillment of the requirements for the Master of Science degree. Present address: Shell Oil Company, 1503 West Ashby, San Antonio, Texas.

[2] The authors wish to express their appreciation to Dr. Claude C. Albritton, Jr., Professor of Geology, Southern Methodist University, who supplied the samples and suggested this series as appropriate for study since it appeared to show gradations between calcitic and dolomitic rocks.

PROPOSED CLASSIFICATION CHART CALCITE DOLOMITE CLAY SERIES

Percent clay	Clay				
100 95	Dolomitic clay	Calcitic dolomitic clay	Dolomitic limy clay	Magnesian clay	Calcitic clay
75	Dolomitic marl	Calcitic dolomitic marl	Dolomitic limy marl	Magnesian marl	Marl
25	Marly dolomite	Marly calcitic dolomite	Marly dolomitic limestone	Marly magnesian limestone	Marly limestone
5	Dolomite	Calcitic dolomite	Dolomitic limestone	Magnesian limestone	Limestone
0	1.00	1.20	2.85	17.67	36.19
	Mole Ratio CaO/MgO				

due in the form of clay, then both the horizontal and the vertical scales are used to obtain the proper name. On the vertical scale, the division between five and 25 percent clay includes a prefix of "marly. . . . " The term "marl" is used between 25 and 75 percent clay while the divisions 75 to 95 percent clay include the term " . . . clay" as a suffix. Rocks having from zero to five percent clay are given Pettijohn's (1949) names while those having 95 to 100 percent clay are termed "clay."

Since modification of Pettijohn's scheme involves percentages and mole ratio, it must be coupled with chemical analysis of calcium, magnesium and insoluble residue present. The analytical methods used in most rock laboratories at present are either very time consuming or else do not have sufficient accuracy for correct classifications.

METHODS OF ANALYSIS

Several rapid but relatively inaccurate methods have been proposed to determine the chemical compositions of carbonate rocks. They include staining techniques and boiling the rock with a known amount of hydrochloric acid and determining the amount of carbon dioxide evolved. The standard classical chemical methods used for determining calcium oxide and magnesium oxide are far too laborious and time consuming for the everyday classification of carbonate rocks.

Banewicz-Kenner (1952) recently proposed a modification of the versenate titration for total hardness in water which is applicable to carbonate rocks. This method is faster and simpler than the classical analytical methods used for determining calcium and magnesium in limestones and gives results of satisfactory accuracy.

By the use of this method it is possible to calculate the mole ratio of calcium oxide to magnesium oxide more easily than by the use of the percentage data, since the ratio of milliliters of titrant for calcium to milliliters of titrant for magnesium gives the mole ratio directly. This may be made the basis for a rapid, simple, and sufficiently accurate classification of the limestone-dolomite series. After analysis, the name of the carbonate rock is determined by reference to the modified Pettijohn scheme and the qualifying adjectives are obtained by examining the insoluble residue.

An even more rapid, but less accurate, method of analysis is available since the actual percentage composition is not

necessary in the classification of the rock. By this method, it is not necessary to know either the weight of sample or the concentration of the versenate. In such a procedure a rock sample is dissolved in hydrochloric acid and two equal volume aliquots are obtained using a pipette. One is titrated for total calcium and magnesium, and the other is titrated rapidly for magnesium in the presence of the precipitated calcium oxalate. Time required for the magnesium titration is thus considerably shortened, but the calcium may be as much as 1.5 to two percent low and the magnesium 1.5 to two percent high. However, this is usually accurate enough for the purpose of classification. With practice an efficient operator could probably reduce this error to less than one percent average. The results of seven samples run by the usual method and by this fast method are shown in table 1. It should be noted that the results by the rapid method did not affect the classification of any of these samples.

TABLE 1.—*Comparison of results by regular and fast titration*

Sample No.	Oxide	Regular titration	Fast titration	Difference
		%	%	
89	Ca	38.91	37.26	−1.65
	Mg	4.79	5.96	1.17
91	Ca	25.81	25.34	−0.47
	Mg	4.44	4.77	0.33
147	Ca	37.53	36.95	−0.58
	Mg	2.87	3.28	0.41
157a	Ca	23.42	22.59	−0.83
	Mg	3.90	4.49	0.59
157b	Ca	23.29	22.25	−1.04
	Mg	3.42	3.93	0.51
310	Ca	29.70	28.89	−0.81
	Mg	19.85	20.41	0.56
1010	Ca	13.06	13.04	−0.02
	Mg	1.69	1.70	0.01

The mole ratio determined by the rapid method does not give percentages of constituents but only an index number that may be used to classify the carbonate material rapidly. The use of this ratio (table 2) reduces the time and amount of laboratory technique involved, and considers only the calcium oxide and magnesium oxide present in the carbonate rock. With experience, the regular method requires an average of approximately one hour of actual laboratory time per sample if a series of ten samples are run simultaneously and the fast titration method requires approximately one-half this time.

All the magnesium is assumed to be in the form of dolomite and any calcium in excess of the amount required for a 1:1 mole ratio with the magnesium is assumed to be in the form of calcite.

APPLICATION TO PERMIAN ROCKS OF WESTERN TEXAS

Most of the carbonate rocks in the Permian of western Texas have been called limestone when actually many of them are dolomitic. King (1948) has noted that the Capitan formation of the Guadalupe Mountains is more dolomitic than calcitic. This fact has long been recognized (Lloyd, 1929, Crandall, 1929, Blanchard and Davis, 1929); yet, the name remains the Capitan limestone, officially and by common consent.

One may argue that limestone should be retained as a class name for all rocks made predominantly of calcite or of the mineral dolomite or of the two mixed in varying proportions. A rock made entirely of the mineral dolomite still contains more lime (30.4 percent) than magnesia (21.9 percent). To call such a rock dolomite is ambiguous as the name of a mineral is thereby given to a rock. Furthermore, there is evidence that many dolomitic rocks originated as calcitic limestones.

On the other hand, rocks with widely varying chemical characteristics should not be lumped into one class name, since

TABLE 2.—*Percentages and mole ratios of the limestone-dolomite series*

Type	% Calcite	% Dolomite	% MgO	Molar Ratio $\frac{CaO}{MgO}$
Limestone	95	5	0 to 1.1	36.19 or over
Magnesian Limestone	90 95	5 10	1.1 to 2.2	36.19 to 17.67
Dolomitic Limestone	50 90	50 10	2.2 to 10.9	17.67 to 2.85
Calcitic Limestone	50 10	50 90	10.9 to 19.7	2.85 to 1.20
Dolomite	10	90	19.7 to 21.9	1.20 to 1.00

this tends to obscure important differences that may be of use in correlations or in the deciphering of geologic history. An excellent illustration of this situation is provided by the Permian rocks of the Malone and Finlay Mountains of southern Hudspeth County, Texas.

In the Malone Mountains the Permian system is represented by 630 feet of interbedded gypsum and carbonate rocks,

TABLE 3.—*Analysis of carbonate rocks from the Briggs formation, Malone Mountains area*

No.	Specimen: Classification in previous reports	Specimen: Classification by chemical analysis	Locality	Molar Ratio CaO/MgO	Analysis: % AI*	% $CaCO_3$	% $MgCO_3$	% other solubles†
			BUFF DOLOMITE MEMBER					
86	Pisolitic limestone	Pisolitic calcitic dolomite	South of Gypsum Switch, Malone Mts.	2.39	0.63	71.85	25.20	2.32
11	Pisolitic limestone	Pisolitic dolomite	From hill at point, 4664 Malone Mts., Fort Quitman Quadrangle	1.19	0.37	59.13	40.95	−0.45
85	Pisolitic limestone	Pisolitic dolomite	South of Gypsum Switch, Malone Mts.	1.05	6.28	51.27	41.04	1.41
7	Limestone	Dolomitic limestone	South of Gypsum Switch, Malone Mts.	9.12	0.52	90.93	8.37	0.18
13	Limestone	Dolomitic limestone	1.6 mi. southwest of Torcer Station, Malone Mts.	8.54	0.87	89.75	8.83	0.55
			INTERVAL BETWEEN BUFF AND BLACK DOLOMITE MEMBERS					
4	Limestone	Dolomite interbedded with gypsum	South of Gypsum Switch, from 310′ in Malone Mts.	0.95	6.30	48.70	42.96	2.04
310	Limestone	Dolomite	Haymon Krupp Oil and Land Co., Briggs No. 1, northwest end of Malone Mts.	1.07	2.86	53.01	41.52	2.61
14	Limestone	Dolomite	Southeastern end of Malone Mts.	1.05	5.17	52.02	41.77	1.04
84	Limestone	Dolomite	Southeastern end of Malone Mts., directly west of U. S. Highway 80	1.03	1.02	54.24	44.13	0.61
83	Limestone	Dolomite	Northwestern end of the Malone Hills	1.10	5.00	53.27	40.62	1.11
82	Limestone	Limestone	Northwestern end of the Malone Hills	89.22	0.48	97.84	0.92	0.76
			BLACK LIMESTONE MEMBER					
20	Limestone	Limestone	Northwestern end of the Malone Hills	65.65	15.26‡	82.83	1.07	0.84

* Ignited acid insoluble.
† Other soluble constituents by difference.
‡ High insoluble due to silicified shell fragments.

TABLE 4.—*Analysis of carbonate rocks from the Leonard series (undivided) of the Finlay Mountains*

No.	Specimen		Horizon in feet below top of exposed section	Molar ratio CaO/MgO	Analysis			
	Classification in previous reports	Classification by chemical analysis			% AI*	% $CaCO_3$	% $MgCO_3$	% other solubles†
93	Pebbly limestone	Pebbly dolomitic limestone	180′	15.81	3.20	90.61	4.81	1.38
139	Pebbly limestone	Pebbly dolomitic limestone	200′	7.98	3.17	84.65	8.91	3.27
143	Limestone	Limestone	300′	38.20	3.18	92.36	2.03	2.43
145	Limestone	Limestone	370′	81.41	5.42	86.49	0.90	7.19
89	Limestone	Marly dolomitic limestone	basal 500′	5.82	12.67	69.44	10.02	7.87
91	Shale	Consolidated dolomitic limestone marl	500′	4.16	36.43	46.06	9.29	8.22
157a	Shale	Consolidated dolomitic limestone marl	500′	4.30	41.91	41.88	8.16	8.05
157b	Shale	Consolidated dolomitic limestone marl	500′	4.82	44.22	41.57	7.15	7.06

* Ignited acid insoluble.
† Other soluble constituents by difference.

collectively referred to as the Briggs formation. Albritton (1938) has recognized three so-called limestone members within the Briggs which he named the Black limestone, Black Brecciated limestone, and Buff limestone members, in order from oldest to youngest. Analyses by the versenate method of specimens from these members and also from the interval of predominantly gypsiferous beds between the upper two of them are given in table 3.

It will be noted that only samples 20 and 82 retain the same names originally given to them while the other samples from the Briggs formation are either calcitic dolomite, dolomite, or dolomitic limestone. It should also be noted that the mole ratio is all that is needed to classify the rock with reference to table 2.

In the Finlay Mountains, seven miles to the north of the Malone Mountains, Albritton and Ham (1941) and Albritton and Smith (1949) measured approximately 1600 feet of Permian rock, which on the evidence of fossils are probably of Leonard age and in part contemporaneous with the section in the Malones. According to them, limestone accounts for about 20 percent of the section, silty shales 55 percent, and limestone conglomerate for 25 percent. Here again classification by chemical analysis shows differences between the rocks called limestone, and indicates that the "silty shale" is actually a consolidated dolomitic limestone marl. The results of the analyses are shown in table 4.

CONCLUSIONS

The versenate method provides a rapid and accurate means of determining calcium and magnesium and hence of classifying carbonate rocks according to Pettijohn's scheme or to the modification of this scheme recommended herein. It is shown that in the Permian rocks of the Malone Mountains, the Black Brecciated limestone is actually a dolomite and the Buff limestone a mixture of calcitic dolomite, dolomite, and dolomitic limestone. Likewise, some of the rocks in the Permian system of the Finlay Mountains that have been called "limestones" are in reality dolomitic limestone, while certain "shales" are consolidated dolomitic limestone marls.

Due to the relative rapidity with which the versenate method can be run, the time factor no longer prevents applying a chemical method of classification to carbonate rocks. By the regular method, it is possible to average one sample per hour if a series of ten samples are run simultaneously while by the rapid method; a single sample requires about thirty minutes.

REFERENCES

ALBRITTON, C. C. JR., 1938, Stratigraphy and structure of the Malone Mountains, Texas: Geol. Soc. America Bull., v. 49, pp. 1747–1806.

ALBRITTON, C. C. JR. and HAM, WM. O., 1941, Stratigraphy and structure of the Finlay Mountains, Texas: abstract Geol. Soc. America Bull., v. 52.

ALBRITTON, C. C. JR. and SMITH, FRED J., 1949, Sedimentary rocks of Permian Age in the Northwestern Marfa Basin, Hudspeth County, Texas: Geol. Soc. America Bull., v. 60, pp. 1869–1990.

BANEWICZ, JOHN J. and KENNER, CHARLES T., 1952, Determination of calcium and magnesium in limestones and dolomites: Anal. Chem., v. 24, p. 1186.

BLANCHARD, W. GRANT JR. and DAVIS, MORGAN J., 1929, Permian stratigraphy and structure of parts of southeastern New Mexico and southwestern Texas: Am. Assoc. Petroleum Geologists Bull., v. 13, pp. 957–995.

CRANDALL, K. H., 1929, Permian stratigraphy of southeastern New Mexico and adjacent parts of western Texas: Am. Assoc. Petroleum Geologists Bull., v. 13, pp. 927–944.

GRABAU, A. W., 1904, On classification of sedimentary rocks: Am. Geologist, v. 33, pp. 228–247.

KING, PHILIP B., 1948, Geology of the southern Guadalupe Mountains Texas: U.S. Geol. Survey Prof. Paper 215, p. 62.

KRYNINE, PAUL D., 1948, The megascopic study and field classification of sedimentary rocks: Jour. Geology, v. 56, pp. 130–165.

LLOYD, RUSSELL E., 1929, Capitan Limestone and associated formations of New Mexico and Texas: Am. Assoc. Petroleum Geologists Bull., vol. 13, pp. 645–658.

PETTIJOHN, F. J., 1948. A preface to the classification of the sedimentary rocks: Jour. Geology, v. 56, pp. 112–117.

———, 1949, Sedimentary Rocks. Harper and Brothers, New York, 526 pp.

RODGERS, JOHN, 1950, The nomenclature and classification of sedimentary rocks: Am. Jour. Science, v. 248, pp. 297–311.

SHROCK, ROBERT R., 1948, A classification of the sedimentary rocks: Jour. Geology, v. 56, pp. 118–129.

VAN TUYL, F. M., 1914, The origin of dolomite: Iowa Geol. Survey, Ann. Rept., v. 25, pp. 251–421.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 51–57
PL. 1, MARCH, 1955

TRANSPORTATION OF ROCKS BY DRIFTWOOD[1]

K. O. EMERY
University of Southern California, Los Angeles, California

ABSTRACT

Driftwood as a rafting agent for rocks is compared to other marine agents in terms of size and abundance of rocks and effective geographical range. It is concluded that driftwood is the chief rafting agent for large erratic rocks in far offshore regions of the tropics. In areas nearer shore and at high latitudes driftwood rafting is probably secondary to other forms of transportation of rocks.

INTRODUCTION

Large erratic rocks are occasionally noted in fine-grained sediments of the present sea floor as well as in ancient strata. The difference in grain size and lithology of the rocks and of their matrix indicates a difference in agent, source, or time of transportation.

Probably the dominant present-day and Pleistocene agent of transportation of erratic rocks to the open sea is that of ice rafting. Ice-floes and icebergs commonly are discolored by large quantities of enclosed sediment which falls to the sea floor when the ice melts (Carsola, 1954). Rocks from this source have long been recognized in marine deposits (Peach, 1912), and above mid-latitudes ice-transported sediment forms extensive and thick layers on the bottoms of the Atlantic Ocean (Bramlette and Bradley, 1941) and of the Pacific Ocean (Menard, 1953).

Turbidity currents also appear to be important contributors of coarse sediment to the sea floor. They are considered responsible for sand layers within muds off California (Shepard, 1951) and in the Atlantic Ocean (Ericson, Ewing, and Heezen, 1952). Scattered pebbles occur in some of these sand beds and many pebbles and cobbles that have been collected from the floor of the Philippine Trench (Bruun, 1951) are ascribed to turbidity currents (Emery and Natland, 1952). The limitations of turbidity currents as to size of rocks and geographical distribution are not yet well known; however, it seems improbable that turbidity currents can transport rocks or large pebbles farther than a few tens of miles beyond the foot of slopes. Moreover, the turbidity currents are probably more capable of depositing gravel within sand layers than of isolated rocks within mud.

Certain animals and plants are able to carry and deposit sporadic rock fragments many miles from the outcrops. Such geological work is well known to have been performed on land by dinosaurs of the Mesozoic (Wieland, 1906) and by the large extinct flightless moa birds of New Zealand. Sand and shells can be carried great distances over water by migrating birds (Sayles, 1931; Teichert and Serventy, 1947), but pebbles and cobbles require larger hosts. Sea lions and some other marine mammals use stones presumably as aids in breaking up fish bones (Emery, 1941; Fleming, 1953), afterward regurgitating them. These stones are abundant on some hauling-out grounds (Fleming, 1951) and possibly a few are released in deep water.

Rafting of rocks by kelp is well known along temperate coasts (Emery and Tschudy, 1941), and Shumway (1953) has attributed to this agency many pebbles and cobbles that were dredged from the deep sea floor off Mexico. Patches of floating kelp carrying rocks have been

[1] Allan Hancock Foundation Contribution No. 150.

noted as far as 300 miles offshore (Menard, 1953), but probably little kelp travels much farther seaward because of the rapidity of decomposition and eating by many animals. Furthermore, the large brown kelps that are chiefly responsible for the rafting (*Macrocystis*, *Pelagophycus*, and *Nereocystis*) are absent in tropical waters at present.

RAFTING BY DRIFTWOOD

Open Sea

Land vegetation was recognized long ago as an agent capable of transporting rocks into the marine environment, but there is little published information on its relative importance as compared to other means of transportation. During their growth trees send their roots into the substrate where they commonly enclose rock fragments. Of some minor interest is the fact that woodpeckers aid by placing pebbles in holes drilled into tree trunks when nuts are not available (Ritter, 1938). If the trees become undermined by stream erosion or are blown over by wind some of the rocks may remain with the trees and in time be floated downstream to the ocean. The large number of trees that can be carried by streams is well illustrated by Mark Twain's stories of piloting on the Mississippi River and by Lyell's (1850) account of a log raft in Atchafalaya River that in 38 years grew to a length of 16 km, a width of 220 m, and a thickness of three m. Along cliffed shores trees are occasionally undermined by wave action and fall directly into the sea (dozens of recently undermined coconut and casuarina trees were noted around the shores of the Hawaiian Islands in 1954); thus, both streams and marine erosion bring trees to the ocean.

Once trees are afloat at sea they are able to travel for great distances with the currents. Rouch (1954) described many examples of "floating islands" made of trees and other vegetation that were sighted far out in the ocean and which had come from the Amazon, Congo, and Mississippi Rivers. Occasionally, such floating trees have been struck by ships at night; thus, they constitute menaces to navigation, particularly for small ships. Some of the trees become waterlogged and sink to the bottom, accounting for wood fragments that have been noted in cores from the floor of the ocean off southern California, the Gulf of Mexico, and elsewhere (F. P. Shepard and Maurice Ewing, personal communications). Sinking is aided by activities of teredos and other wood borers, whose holes have even been noted in logs that sank in Eocene seas of California (Szatai, in preparation).

Many trees remain afloat so long that they eventually are cast ashore on distant islands where their wood was formerly and locally still is used by the natives for boats or houses. The writer found a large sawed log, probably Douglas fir from Oregon or Washington, cast ashore on Rongelap Atoll in the Marshall Islands and thoroughly encrusted and riddled by marine borers. Another was seen on Johnston Island and about 10 more on various islands of the Hawaiian Chain. Other similarly bored Oregon logs were noted on the shores of the Hawaiian Islands by Guppy (1906). In the southern hemisphere many logs that had floated to the Tuomoto Islands probably from South America had been in the water so long and were so completely bored that they were of no value for boat building (Mr. Yvor H. Smitter, personal communication).

In a few instances floating trees have been observed to hold rocks and other debris in their roots. Brooks (1875) described a 50-meter tree believed to be from Oregon that drifted past Maui in the Hawaiian Chain carrying several tons of clayish earth embedded among its roots. In 1950 Smitter aboard the schooner *California* saw a kauri tree afloat in the Gulf of Papua. This tree was three meters in diameter and floated in a vertical position with the top 25 meters out of water and the lower 10 meters under

water. Held by the roots was a boulder three or four meters in diameter whose weight served as a keel to hold the tree upright. The sighting was about 150 miles off the Fly River, which was probably the source as it was in flood and carrying great quantities of logs and debris. The tree had been in the sea long enough, however, for boring organisms and barnacles to become established.

Many similarly laden trees have been washed ashore on islands and coral reefs where their loads of rock were formerly prized for instrument sharpening (Chamisso, 1821; Chamisso, 1902?; Wood-Jones, 1912; Andrée, 1920). In fact, at Tarawa there was a native term meaning "basaltic stones in the roots of trees drifted" (Pickering, 1876). Described in somewhat more detail by Hartzer (1900) were pines a meter in diameter cast ashore on Nonouti Island that carried by their roots stones of fine-grained basalt of all sizes; he believed that the trees came from New Zealand 1200 miles away. Of interest also is the fact that tree trunks that drifted at least eight miles from the Australian mainland to Low Isles of the Great Barrier Reef rafted live frogs (Fairbridge and Teichert, 1948) as well as rocks (Fairbridge, personal communication).

Occasional loose stones picked up on beaches of coral islands were believed by Darwin (1887) to have been rafted by driftwood, though no trace remained of the tree itself. Many workers have reported the presence of pieces of volcanic rock at Rose Atoll (Couthouy, 1842; Wilkes, 1845; Dana, 1849; Pickering, 1876; Schultz, 1940; and Sachet, 1954).[2] Until recently the favored origin was that of reworking from submarine outcrops, but now Mr. Gilbert Corwin (personal communication) has concluded that the unusual mineral composition of the rock may require distant transportation by driftwood. In 1953 Dr. R. S. Dietz found a 12 cm sub-rounded piece of rhyolite on Wake Island and Dr. Maxwell S. Doty found a 30+ cm piece of hard fine-grained basaltic tuff imbedded in beachrock on Johnston Island. In neither area do non-calcareous rocks crop out subaerially, and rhyolite certainly is rare in the central Pacific Ocean. Doubtlessly, many other such stones remain unnoticed on other shores. Some stones probably have come from ship ballast (Oldham, 1895) or other human sources, some may be reworked from submarine outcrops (Couthouy, 1842), but others cannot be so explained.

[2] Some of these references were kindly contributed by Marie-Hélène Sachet who encountered them during her compilation of a bibliography on flora of atolls.

Southern California

Owing to the lack of forests and to the low rainfall in southern California, particularly during recent years, streams of this area probably contribute fewer trees to the ocean than do those of other regions. There has also been little recent coastal erosion. Nevertheless, a more or less systematic examination of driftwood on some of the beaches during the period 1950 to 1953 resulted in the recovery of 12 examples of rafted rocks by Mr. A. L. Simpson, who kindly made his data available for this report. Two other examples from earlier casual finds by the writer (La Jolla and Kauai) are also listed in table 1. The frequency of visits and the number of beaches that were examined during the three-year period are such that probably only about one percent of the tree-rafted rocks that were stranded on the shores of southern California were found. An unknown additional number drifted seaward and out of the area.

The identified driftwood hosts were manzanita and juniper, both of which are common in the region. Local derivation also is indicated by absence of barnacles and other encrusting organisms except on one example from Malibu Beach. Rock fragments carried by an individual piece of driftwood ranged in number from one to twenty-five. The

TABLE 1.—*Characteristics of driftwood and attached rocks*

Location	Driftwood			Rocks		
	Length, cm.	Diameter, cm.	Kind	Diameter, cm.	Shape	Kind
1 Malibu Beach	50	15	Manzanita	3.0	SA	Meta-diorite
2 Malibu Beach	30	16	Manzanita	1.3	A	Shale
				2.2	A	Shale
3 Malibu Beach	70	5	Manzanita	2.2	SA	Rhyolite tuff
4 Playa del Rey	100	50	—	1.0	Twenty-five pebbles	
5 Malaga Cove	75	35	—	4.0	SA	Quartzite
6 Portuguese Bend	90	20	Juniper	10.5	A	Lamprophyre
7 Newport Beach	85	25	Manzanita	5.5	SA	Granite gneiss
				3.0	A	Granite gneiss
				1.7	A	Granite gneiss
				1.5	A	Granite gneiss
8 Corona del Mar	60	15	Manzanita	4.0	A	Schist
				4.0	A	Schist
9 Laguna Beach	60	15	—	5.0	A	Granodiorite?
10 Oceanside	70	50	—	3.0	A	Granodiorite?
11 La Jolla	100	40	—	20.0	A	Igneous rock
12 Kauai, T. H.	250	60	—	15.0	R	Basalt
13 Malibu Beach	15	20	—	12.0	SR	Quartzite
				3.0	SR	Basalt
14 Malibu Beach	50+	30	Bored	3.0	SR	Basalt

largest is about 20 cm long. Characteristically, the rocks are angular and fairly fresh and unweathered in appearance. The lithology is highly varied (table 1) but, although probably all of these types of rock occur in southern California, none were recognized as diagnostic of the region.

Geological Record

Erratic rocks have been reported within ancient sedimentary strata, chiefly coals, from Britain (Spencer 1887; Stutzer and Noé, 1940; Whittle, 1943; Dix, 1944—short bibliography; and Hawkes, 1951), from elsewhere in Europe (Makowski, 1935; Turlei, 1941), from Australia (Fairbridge, 1952, 1953), and from the United States (Andrews, 1872, Marsh, 1872; Hicks, 1879; Lesley, 1884; Orton, 1892; Dana, 1895; McCallie, 1903; White, 1915; and Price, 1932—short bibliography). Curiously, most of the erratics in American coal beds are quartzite. Andrews had proposed a possible glacial advance to account for boulders in Pennsylvanian coal in Ohio, but Marsh pointed out that rafting by tree roots during a freshet is more reasonable. Similarly, erratic boulders in the Permian and Cretaceous strata of Australia, formerly thought to indicate gla-

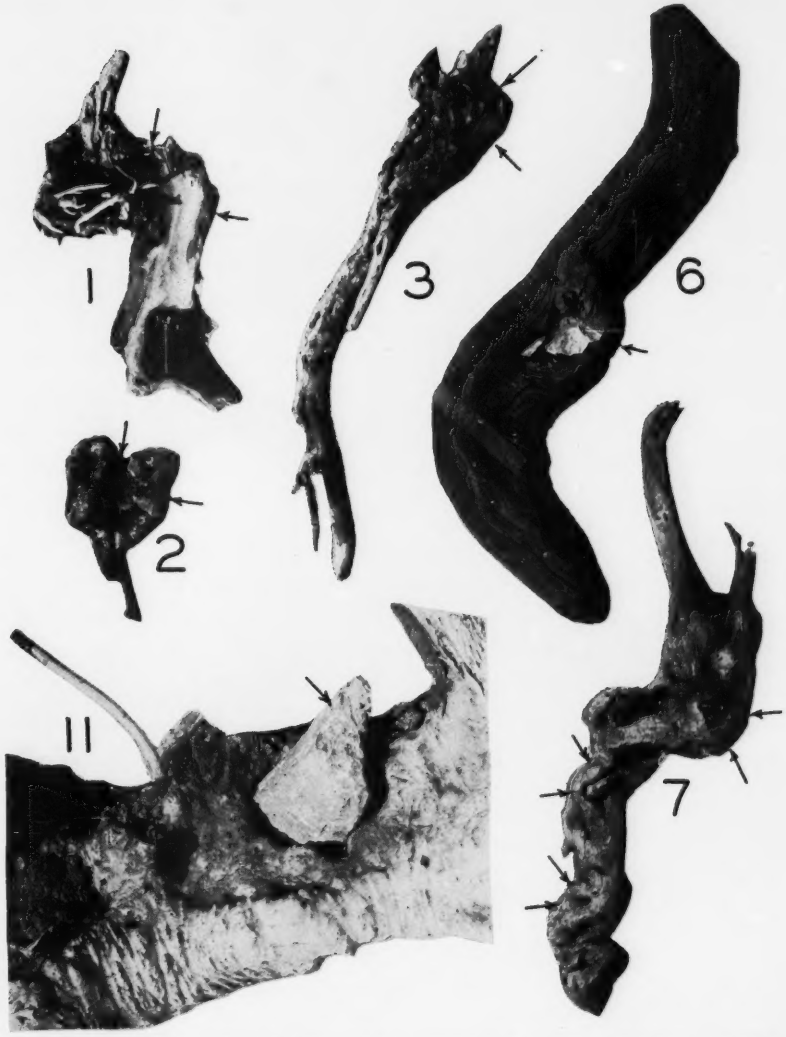


PLATE 1.—Some examples of driftwood that contain rock fragments found on beaches of Southern California. Numbers are those of Table 1. Rocks are indicated by arrows. About 1/10th natural size.

ciation, were recently attributed by Fairbridge to tree rafting because of their close association with coal beds. Most of the other authors also considered that the erratic rocks which they described had been rafted to swamps by floating trees.

GEOLOGICAL SIGNIFICANCE

More rafting of rocks by driftwood occurs than is generally realized. Many instances have been noted under present conditions as well as in the geological record. Larger individual pieces and more numerous clusters of rock can be carried by floating trees than by other plants or by animals. Trees also can carry rocks farther seaward than can other plants and animals and into more tropical water than can be reached by either icebergs or kelp.

REFERENCES

ANDRÉE, K., 1920, Geologie des Meeresbodens. Leipzig, Gebrüder Borntraeger, 689 pp.

ANDREWS, E. B., 1872, Geological survey of Ohio: Amer. Naturalist, v. 6, pp. 289–292.

BRAMLETTE, M. N. and BRADLEY, W. H., 1941, Geology and biology of North Atlantic deep-sea cores: Pt. 1, Lithology and geologic interpretations: U.S. Geol. Survey Prof. Paper 196, pp. 1–34.

BROOKS, C. W., 1875, Report of Japanese vessels wrecked in the North Pacific Ocean from the earliest records to the present time: Proc. California Acad. Science, v. 6, pp. 50–66.

BRUUN, A. F., 1951, The Philippine Trench and its bottom fauna: Nature, v. 168, no. 4277, pp. 692–693.

CARSOLA, A. J., 1954, Recent marine sediments from Alaskan and Canadian Arctic: Am. Assoc. Petroleum Geologists Bull., v. 38, pp. 1552–1586.

CHAMISSO, A. VON, 1821, Remarks of the naturalist of the expedition; in Otto von Kotzebue, "A voyage of discovery into the South Seas and Beerings Straits for the purpose of exploring a north-east passage undertaken in the years 1815–1818," London, v. 3, 442 pp.

———, 1902?, Sämtliche Werke, v. 3: Reise um die Welt mit der Romanzoffischen Entdeckungs-Expedition in den Jahren 1815–1818 auf der Brigg *Rurick*, Kapitän Otto v. Kotzebue, editor: Adolf Bartels, Leipzig, Hesse Co., 242 pp.

COUTHOUY, J. P., 1842, Remarks upon coral formation in the Pacific: Boston Jour. Nat. History, v. 43, pp. 66–105, 137–162.

DANA, J. D., 1849, Geology: U.S. Exploring Expedition, v. 10, 756 pp. (not seen).

———, 1895, Manual of geology, 4th edition, New York, 1057 pp.

DARWIN, C., 1887, Naturalist's voyage around the world. 2nd. edition, D. Appleton & Co., New York, 519 pp.

DIX, E., 1944, On two rounded boulders from an anthracite seam, South Wales: Geol. Mag., v. 81, pp. 127–128.

EMERY, K. O., 1941, Transportation of rock particles by sea-mammals: Jour. Sedimentary Petrology, v. 11, pp. 92–93.

EMERY, K. O. and NATLAND, M. L., 1952, Our shrinking globe—a discussion: Geol. Soc. America Bull., v. 63, pp. 1069–1072.

EMERY, K. O. and TSCHUDY, R. H., 1941, Transportation of rock by kelp: Geol. Soc. America Bull., v. 52, pp. 855–862.

ERICSON, D. B., EWING, M., and HEEZEN, B. C., 1952, Turbidity currents and sediments in North Atlantic: Bull. Am. Assoc. Petroleum Geologists Bull., v. 36, pp. 489–511.

FAIRBRIDGE, R. W., 1952, The Permian of southern Western Australia: Symposium sur les Séries de Gondwana publié par le XIX Congrès Géologique International, Alger, pp. 136–146.

———, 1953, Australian stratigraphy, 2nd. edition: Univ. of Western Australia, Nedlands (mimeographed).

FAIRBRIDGE, R. W. and TEICHERT, C., 1948, The Low Isles of the Great Barrier Reef: a new analysis: Geog. Journal, v. 111, pp. 67–88.

FLEMING, C. A., 1951, Sea lions as geological agents: Jour. Sedimentary Petrology, v. 21, pp. 22–25.

———, 1953, The geology of the Snares Islands: Pt. I General Geology: Sci. Results of the New Zealand Sub-Antarctic Expedition, 1941–45, v. 13, pp. 9–32.

GUPPY, H. B., 1906, Observations of a naturalist in the Pacific between 1896 and 1899: II Plant dispersal, MacMillan & Co., Ltd., New York, 627 pp.

HARTZER, F., 1900, Les iles Blanches des Mer du Sud. Paris, 345 pp.

HAWKES, L., 1951, The erratics of the English Chalk: Geologists' Association, London Proc., 62, pt. 4, pp. 257–258 (not seen).
HICKS, L. E., 1879, Bowlders in coal: Am. Jour. Science, 3rd series, v. 17, pp. 68–69.
LESLEY, J. P., 1884, On quartz pebbles found in coal near Cannelton, Beaver Co., Pa.: Am. Philo. Soc. Proc., 21, p. 344.
LYELL, C., 1850, The principles of geology. 8th edition, John Murray & Co., London, 811 pp.
MAKOWSKI, A., 1935, Galets donc les veines de la houille de la mine Emma dans le district de Rybnik en Haute-Silésie: Poland, Serv. Géol., C. R., no. 42, p. 8 (not seen).
MARSH, O. C., 1872, Boulders in coal: Am. Naturalist, v. 6, p. 439.
MCCALLIE, S. W., 1903, An erratic bowlder from the Coal Measures of Tennessee: Am. Geologist, v. 31, pp. 46–47.
MENARD, H. W., 1953, Pleistocene and Recent sediment from the floor of the northeastern Pacific Ocean: Geol. Soc. America Bull., v. 64, pp. 1279–1294.
OLDHAM, C. F., 1895, The topography of the Arabian Sea in the neighborhood of the Laccadives: Jour. Asiatic Soc. Bengal, v. 64, pt. 2, pp. 1–14.
ORTON, E., 1892, On the occurrence of a quartz bowlder in the Sharon Coal of northeastern Ohio: Am. Jour. Science, 3rd series, v. 44, pp. 62–63.
PEACH, B. N., 1912, Report on rock specimens dredged by the *Michael Sars* in 1910, by H.M.S. *Triton* in 1882, and by H.M.S. *Knight Errant* in 1880: Royal Soc. Edinburgh Proc., v. 32, pp. 262–291.
PICKERING, C., 1876, Geographical distribution of animals and plants: U.S. Exploring Expedition under Wilkes, v. 19, pt. 2, 524 pp.
PRICE, P. H., 1932, Erratic boulders in Sewell Coal of West Virginia: Jour. Geology, v. 40, pp. 62–73.
RITTER, W. E., 1938, The California Woodpecker and I. Berkeley, California Univ. Press, 340 pp.
ROUCH, J., 1954, Les îles flottantes: Archiv für Meteorologie, Geophysik und Bioklimatologie, series A, v. 7, pp. 528–532.
SACHET, MARIE-HÉLÈNE, 1954, A summary of information on Rose Atoll: Pacific Science Board, Atoll Research Bull., no. 29, 25 pp. (mimeographed).
SAYLES, R. W., 1931, Bermuda during the Ice Age: Am. Acad. Arts Sci. Proc., v. 66, no. 11, pp. 381–468.
SCHULTZ, L. P., 1940, The Navy surveying expedition to the Phoenix and Samoa Islands, 1939: Smithsonian Explorations, 1939, pp. 45–50.
SHUMWAY, G. A., 1953, Rafted pebbles from the deep ocean off Baja California: Jour. Sedimentary Petrology, v. 23, pp. 24–33.
SHEPARD, F. P., 1951, Transportation of sand into deep water: Soc. Econ. Paleont. and Mineralogists, Sp. Publ. 2, pp. 53–65.
SPENCER, J., 1887, On boulders found in seams of coal: Quart. Jour. Geol. Society, v. 43, pp. 734–735.
STUTZER, O. and NOÉ, A. C., 1940, Geology of coal. University of Chicago Press, 461 pp.
SZATAI, J. E. (in preparation), Geology of the eastern part of Ridge Basin, California: Doctoral Dissertation, University of Southern California.
TEICHERT, C. and SERVENTY, D. L., 1947, Deposits of shells transported by birds: Am. Jour. Science, v. 245, pp. 322–328.
TURLEI, G. F., 1941, A finding of a garnet gneiss boulder in the coal seam K, of the series C^{s}_{2} of the Donetz basin: Acad. Sci. URSS, C. R. (Dokl.), v. 31, no. 2, pp. 133–134 (not seen).
TWAIN, MARK, 1944, Life on the Mississippi (collected stories). Heritage Press, New York, 418 pp.
WHITE, C. D., 1915, The occurrence of transported bowlders in coal beds: Washington Acad. Sci. Jour., v. 5, p. 407.
WHITTLE, W. L., 1943, The occurrence of quartzite boulders in the Stanley main coal at Nostell, near Wakefield: Yorkshire Geol. Soc. Proc., v. 25, pt. 2, pp. 140–141, 175–189 (not seen).
WILKES, C., 1845, Narrative: U.S. Exploring Expedition, v. 2, p. 64.
WIELAND, G. R., 1906, Dinosaurian gastroliths: Science n.s., v. 23, pp. 819–821.
WOOD-JONES, F., 1912, Coral and atolls. Lovell Reeve & Co., London, 392 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 58–59
MARCH, 1955

A SPOT TEST FOR DOLOMITIC LIMESTONES

VIRGIL I. MANN
University of North Carolina, Chapel Hill, North Carolina

ABSTRACT

A technique is presented for the separation in the field of dolomitic limestones from high calcium limestones. The procedure requires an application of two solutions on a fresh rock surface. The rate at which a blue color is precipitated will separate dolomitic limestones from other non-magnesium carbonates. A purple color indicates a lack of magnesia.

In many geological sections which are high in carbonates, it is desirable to separate each of the units in the field. Most techniques used to separate dolomitic limestones from metallurgical grade limestones require laboratory tests varying from straight solution in acid to complete quantitative analysis. Whereas laboratory tests are conclusive, they require excessive storage space for equipment and extended amounts of time, two luxuries most field geologists cannot afford. The following technique was devised to permit a field geologist to identify varieties of dolomitic limestone and pure calcium carbonate beds at the outcrop.

The procedure involves the application of two solutions on a fresh rock, surface. First a drop of dilute HCl is applied to a clean rock surface. After all vigorous reaction has ceased, a drop of an alkaline solution of p-nitrobenzene-azoresourcinol is introduced into the earlier drop. If the drop turns a blue color in 30 seconds, the rock fragment is high in available MgO. Various intensities of blue develop with decreasing quantities of MgO, until on a carbonate with no MgO, only a violet color is seen. As any trace of the blue color will be concentrated with evaporation the reaction must be observed within the first minute after application of the dye. If the acid fails to react with the rock because if its high magnesia content, a pale yellow color results.

Reagents are those suggested by Feigl (1946); however, two of his proposed solutions are combined, and the concentration of the other is altered. The acid is the common one used by geologists, 10 percent (by volume) HCl. The dye is prepared by dissolving .002 grams of p-nitrobenzene-azoresourcinol in 100 cc of 2N sodium hydroxide.

The weak acid will attack a fresh rock surface, putting into solution both calcium and magnesium ions. Further, the acid by its reaction will indicate how much pure calcium carbonate is in the rock. Thus pure dolomite can be separated from pure calcium limestone at this step; however, the straight acid reaction gives indeterminate results when MgO is less than 10 percent and when magnesium salts are in solid solution.

The organic dye is quickly adsorbed by $Mg(OH)_2$ giving rise to a distinctive blue color. This readily discernible color is distinct from the violet of the non-adsorbed dye. A magnesium ion in the acid solution is converted to the hydroxide by application of the alkaline dyestuff reagent, and it adsorbs the dye. The amount of magnesium present determines the intensity of blue color.

Feigl (1946), claims a sensitivity of .5 gamma for the spot test, and as most limestones have at least a trace of magnesium, a mild blue color is nearly always seen. The longer the solution is permitted to evaporate, the more will be concentrated the trace quantities of mag-

nesium. Thus the reaction should be observed prior to appreciable evaporation.

The procedure was tested in the field for three months with a laboratory control of quantitative analyses. Whereas the field test never became completely quantitative, at least four groups of carbonates could be separated at the outcrop by this method. They were: (1) specimens with greater than 30 percent MgO; (2) those having between 10 and 30 percent MgO; (3) rocks having an MgO content between one and 10 percent; and (4) those having less than one percent MgO. At the time of the field work, those categories were the desired ones, and thus no further subdivisions were attempted.

The technique was found to be most useful in areas where contacts between formations were poorly exposed, or in exposures where lithographic boundaries were not visible to the eye. By modifying the procedure to suit a specific area, a geologist may use the technique advantageously in mapping boundaries between relatively pure lime carbonates and magnesium carbonates in the field, as well as subdividing the magnesium carbonates into selected varieties.

REFERENCE

FEIGL, F., 1946, Qualitative analysis by spot tests (Translated by R. E. Oesper). Elsevier Publishing Co., Inc., New York. 574 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 60–66
MARCH, 1955

ORIGIN OF STYLOLITES: A DISCUSSION

B. M. SHAUB
Smith College, Northampton, Massachusetts

ABSTRACT

A critical examination of the paper by Marsh (1867) shows clearly that he did not originate the contraction-pressure theory for the origin of stylolites as claimed by Prokopovich (1952).

An examination of Gümbel's papers of 1882 and 1888 shows that he based a preliminary phase of his theory upon the compaction of the sediments and the drying out and *cracking* of the clay layers between the *still plastic* calcareous beds above and below the clay. Gümbel's theory is essentially that of Marsh after obtaining the small pieces of clay which functioned in the same manner as the fossils in Marsh's theory.

Hence, neither of these investigators proposed the contraction-pressure theory as claimed by Prokopovich.

An examination of the solution theory described by Prokopovich shows it to be completely inadequate to produce stylolites and that none of the common and outstanding features of stylolite columns and seams can be logically explained by this theory.

In a recent paper Prokopovich (1952) proposes a new solution theory, for the origin of stylolites, in which solution is supposed to occur in the surface layers of the recently precipitated and soft calcareous deposits on the bottom of the sea, or within the mass of the unconsolidated sediments. The basis for his deductions is the variation of the CO_2 content and corresponding pH of sea water with depth.

In addition he makes a very brief review of the existing theories for the origin of stylolites. His views and statements seem to be at considerable variance with the classification of the several theories made by Stockdale (1922) who grouped the then existing theories in several categories. These groups, with the originator of each theory, are listed as follows: Organism theory by Eaton (1824); crystallization theory, Bonnycastle (1831); erosion theory, Plieninger (1852); gas theory, Zelger (1870); bitumen theory, Alberti (1858); pressure theory, Quenstedt (1837); and the solution theory, Fuchs (1894).

In connection with the previous theories, Prokopovich, (p. 212), says "most of the ideas proposed excepting for the contraction-pressure and the pressure-solution hypotheses, have historical importance only and are not discussed in this paper. The contraction-pressure hypothesis was proposed by Marsh (1867), Gümbel (1882, 1888), and others." The views of these investigators and writers have been included by Stockdale (1922) in the category of "pressure theories," apparently on the basis of the statements made by these writers concerning their investigations and ideas which they had presented for the origin of stylolites. In regard to the views of Marsh one may quote his beliefs as given in 1867. On page 138 he says,

"A comparison, however, of the various forms of this structure as they occur in different formations, and at widely separated localities, clearly show that all have been produced by some common cause, which was not dependent on local influences or conditions. The subject of the present paper was to prove that this structure in all its various modifications was the simple result of *pressure*. The author had carefully examined many typical localities in this country and in Europe, and found at each conclusive evidence in favor of this explanation, which satisfactorily accounts for all the known phenomena of the structure. . . . Nearly all the separate columns, moreover, have on their

summits *a fossil shell, or the inorganic substance, which has accurately determined their shape*, and above this a rounded or pointed cap of shale, evidently identical with the layer already mentioned, and separated from it when the strata settled during consolidation."

In a more detailed statement Marsh says, p. 139,

"let us first suppose a quantity of fine carbonate of lime, sufficient when consolidated to make a thick bed of limestone, slowly deposited under water; and while still, soft (comma appears to be misplaced, B.M.S.) shells and other organic substances scattered over it, and the whole then covered with a very thin layer of argillaceous mud. If, after this, the deposition of calcareous matter proceeds, gradually forming a second bed, its increasing weight will slowly condense the bed below. The shells beneath the clay layer will offer more resistance to the vertical pressure than the material around them, and hence the latter will be carried downward more rapidly, thus leaving columns projecting into the bed above, each protected by its covering, and taking its exact shape from its outline. That this must have been essentially the method of formation, every typical locality of stylolites, if carefully studied, will afford ample evidence.

"The immediate cause of the formation of columns under the above circumstances is clearly a difference of resistance to pressure between the shell, supported by material beneath it, and the surrounding mass. The reason why the shell resists the pressure more effectually than the substance around it may be owing first to its form, which, when its convex side is upward, enables it to act as a wedge, thus overcoming in part, the cohesion of the material above it; secondly, to its weight, which would slightly condense the plastic mass beneath it, and thus secure a more firm support; or thirdly, to its being an organic substance, which, like the nucleus of a concretion, has attracted to itself and consolidated the particles of carbonate of lime beneath it, but not those above, owing to the intervening argillaceous layer. Any one of these causes would, doubtless, be sufficient to produce the superior density required to start a column, and this would at once have its farther progress facilitated by a cap of mud formed above the shell, thus rendering the summit of the column more convex, and hence diminishing the effective pressure."

It will be noticed from the above detailed description that Marsh viewed the column as a harder and more rigid mass than the surrounding material. And further it is this greater rigidity together with the spherical shape and possibly the lubricating property of the clay cap which assists in causing the penetration of the more rigid column under pressure which was supposedly derived from the weight of the overlying deposits. In contrast, the contraction-pressure theory of Shaub (1939) requires a *plastic* column (or penetrating part) to move into a zone or zones of reduced pressure created by contraction in the layer or zone penetrated due to the dewatering of the material which rendered it firmer and initiated tension stresses therein by contraction. It can be seen at once that there is no resemblance of the one theory to the other.

A further and careful search of Marsh's paper fails to find the words, contraction or shrinkage, or any synonym of these words which was used by him to infer or imply that the initiation and/or continued development of stylolites depended on low tension stresses caused by shrinkage in plastic materials. Hence Prokopovich's statement as quoted above regarding Marsh as being the originator of the contraction-pressure theory is without foundation or support.

More than a decade after the writer had investigated cone-in-cone and stylolite structures and had published his views concerning them (1937, 1939) he obtained a copy of Gümbel's papers of 1882 and 1888 and had them translated. The first of Gümbel's papers appeared fifteen years after that of Marsh quoted above and like Marsh he placed a great deal of emphasis on the requirement, not

only of fossils, but of other hardened material as the basic features in the formation of the stylolites by the pressure of the overlying beds.

Gümbel appears to have been a keen observer of the stylolites in their environment. He described the appearance of crystalline substances between the columns and the enclosing rock as had others before him, Bonnycastle (1831); Vanuxem (1838, 1842); Emmons (1842); Hall (1843); Rossmässler and Cotta (1846); Meyer (1862); and Hunt (1863). These writers looked upon the crystallized materials about the columns as the *cause* of the stylolitic process rather than a subsequent development as did Gümbel who regarded the crystalline materials as a late development in open spaces about the columns due to drying out of the entire rock mass during consolidation. He also observed the occasional ridges which are transverse to the column striations and likened them to raised ridges resembling those produced by touching clay and breaking the contact. Similar ridges were observed by the writer at Lockport, N. Y., in 1936 and were photographically illustrated and described by him as *adhesion ridges* in 1939.

Gümbel's description (1882, p. 646) of the origin of stylolites follows.

"As far as the explanation of the formation of stylolites, according to this short description of their outward appearance is concerned, there can be no doubt that the stylolites, when the rock-mass surrounding them solidified, originated at a time when the mass still possessed a certain degree of plasticity, that is, was not yet dried out and was subject to the great pressure of rock material which was storing up. The stylolites originated within several layers which lay one upon another, which were deposited in the form of a lime sludge, and which were separated by layers of clay and marl. With the unequal state at the time of drying out and solidifying the layer of clay and marl contracted, became cracked, and split into little pieces. As a result the balance which had existed between the two layers of lime which rested on each other was disturbed. The upper mass of lime exerted pressure on that lying under it, and sank in correspondence with diminishing space which occurred with the drying out process. As a result it caused individual smaller parts of the underlying mass, which were separated out by the breaking up on the clay-layer to move upward. The smaller mass was thus forced to yield to the pressure of the larger. It could only give way by moving upward, since the under-layer prevented any movement downward. Through this reciprocal movement, the sinking of the main mass and ascending of the small cut up parts, there occurred the conical interlocking of the stylolites with the enclosing rock. Through the movement and penetrating action of the shell or '*Thonschieferscholle*' the channelling and lengthwise striations of the stylolites were formed according to their outlines. The piece of clay which was separated by the tearing up on the lower layer of clay appears as the caps of the stylolite and the little particles of clay which separated off during the ascent are the clay coating of the stylolite.

"I have tried to imitate this occurrence artificially. I covered a half-soft mass of so-called painters chalk, mixed with just a little clay, with a very thin layer of strongly colored clay. Upon this I laid a heavy slab of lead which was provided with holes at several points. Over this I then spread a specially colored layer of lime sludge.

"The weight of the lead slab caused the latter to sink. Corresponding to this sinking, columnar shafts, channeled according to the outline of the holes and striated lengthwise, were forced out of the underlying mass through the holes in the lead slab and pressed into the mass lying upon the slab. Here also the particles of clay formed the cap, and the sides were coated similarly with a covering of clay. After drying out I had little columns, similar to stylolites, which were easily distinguishable by the color, and which had been pushed up into the upper layer." (Translation by Lois Leggett.)

It is quite obvious that Gümbel placed considerable emphasis on the *cracking* of the clay seams as the result of its "drying out" during consolidation. He carries the

shrinking to the extent of cracking the clay layer into "kleine stücken," *small pieces*, in order to place the material of the clay cap in the same category as fossils in the actual development of stylolites by pressure on still plastic lime muds. It is difficult to understand how he could envisage the breaking up of the clay seam by drying out when it was in contact with the plastic marl above and below.

It will be noted that in previous descriptions of the contraction-pressure theory, originated by Shaub (1939), the phenomenon of contraction or shrinkage during the dewatering of the lime sediments, along a clay seam or other line or zone of differential contraction, is in the still plastic material. The clay has never been described as having been cracked in any way, instead, it is undoubtedly carried ahead of the penetrating "column" from the lower bed by the shearing action as it entered a localized reduced pressure zone, in the overlying lime bed, caused by the contraction forces in the base of the overlying bed. The penetration progresses contemporaneously with the dewatering, contraction and plastic flow from the lower bed under the differential pressure of the overlying beds and that created by the tension stresses within the lime muds due to their loss of water.

The two conceptions for the development of stylolites are different and cannot be reconciled as one and the same; and the distinction is even more clearly expressed in Gümbel's later paper of (1888) in which he stated,

"if we hold to the idea that the stylolites originated exclusively by means of pressure of the superimposed mineral material on a layer of marl solidified in a more crust-like condition, this layer covering a deeper bed of mineral, and that the pressure crushed and cut up the marl crust so that individual little pieces of marl sank into the half-soft bed of lime beneath, while at the same time the mineral matter of the layer which was originally above the marl pressed down into the space created by the sinking marl-pieces in a sidewise direction, and that in the downward direction, the marl piece was diverted sideways and often actually horizontally in the direction of least resistance and was able to produce a horizontally extended stylolite." (Translation by Lois Leggett.)

In his second paper Gümbel reiterates the workings of his pressure theory and extends it to account for horizontal stylolite columns or vertical and inclined seams. His theory is essentially that of Marsh enhanced by the added variation of the supposed shrinking of the clay layer so that the pressure of the overlying beds could break it into the "little pieces" necessary for initiating the development of the columns by pressure and to provide the caps for them in very much the same manner that Marsh used the fossils. Hence Gümbel's theory actually supplements that of Marsh and his experiment, which he apparently considered as being successful, relied entirely on the pressure of the heavy lead plate containing a number of holes which, in some manner, corresponded to the "little pieces" of the broken clay layer, and through the action of pressure *alone* he obtained "stylolites." From the writings of Gümbel and his experiment it is difficult to see how Prokopovich can claim that Gümbel proposed the contraction-pressure theory for the origin of stylolites. Both the theory of Marsh and that of Gümbel, with its variations from the former, are certainly to be classed with the pressure theories as they have previously been known and there should not be read into them subsequent views and developments.

It is hoped that the above discussion will clear any confusion that may exist between the earlier *pressure* theories and the *contraction-pressure* theory.

In the same paper quoted above, Prokopovich presents a new concept of the solution theory based on the variation of the solubility of sea water with the variation of the carbon dioxide content of the water and the corresponding

pH of the sea water with depth. On examination of the diagram on which Prokopovich bases his theory (Fig. 9, p. 219) one will observe that for *any given depth* of sea water there is no indicated change in the CO_2 vapor pressure and the corresponding pH of the water; consequently the solubility of calcium carbonate by the sea water at any depth is constant; and as the depth of the oceans remains approximately the same, solution could not occur according to this principle. It appears, therefore, to the writer that one cannot claim that a marked solution can occur on the ocean bottom at any place according to the relationships shown by the diagram. The possible effect of plankton on the content of the carbon dioxide in sea water is also discussed by Prokopovich. The variable effect from this source would no doubt be negligible, for plankton inhabit the upper layers of water, and if any effect were produced it should be seasonal and cyclic and one should observe some rhythmic structure in limestones in general. Effects demonstrated to be directly connected to plankton have apparently not been recorded.

In regard to the operation of his theory for the development of stylolites, Prokopovich says, (p. 219)

"because sea water can attack all surfaces of the columns an insoluble clay skin remains on both sides and on the top of the columns. Curved stylolites, columns with narrowed bottoms and undulation seams could be produced by the solution of walls, movement of water, and the force of gravity. The striated surfaces of columns may have originated in a similar way to those on earth pillars. Fossils and concretions may remain as a resistant covering during the formation of such stylolites similar to the covering of pinnacles. . . . Many of the seams were developed on the sea floor and were, therefore, parallel to the bedding, but solution could also take place below the sea floor in the muds."

Stylolite seams along any horizon appear always to be limited to a rather small areal extent as shown by the exposed seams in limestone quarries and by those in the Tennessee "marble" which are well displayed in many public buildings. To produce stylolites on such limited areas on the sea floor according to Prokopovich's theory would require a most improbable set of conditions where there would be many relatively small areas over which the water would be dissolving the lime muds while over nearby areas deposition may be presumed to be continuing. Such conditions would have to exist for a rather long period to effect the solution required to produce the longer columns. The dissolved materials would have to be removed by outgoing currents while other currents having the ability to dissolve the lime muds were being brought into the small areas undergoing solution. The movements and varying solubilities within ocean waters certainly would not be so restricted or selective for the movement in these waters is sufficiently active and variable to keep the composition of the vast mass of the ocean water nearly constant throughout its extent.

Another phenomenon which would be a feature of stylolites formed on the sea floor by solution of the surrounding material would be the equal stratigraphic height or level of the tops of many of the columns. As the solution continues downward other resistant layers should initiate additional groups of neighboring columns having tops at the same level. If stylolites originated by solution of the lime muds on the ocean floor, then the shorter columns would have the thicker clay caps and the longer columns would be essentially free from a capping. To the writer's knowledge the above features have never been recorded by students of stylolites.

In order to produce columns, which in the hardened rock would have a length of 12 to 18 inches, the soft unconsolidated columns formed on the ocean floor would have to be two to three feet, or greater, in length. The newly precipitated material would probably be soft

enough to be easily extruded between the fingers and lack sufficient strength to support such a long column; hence there should be abundant examples of collapsed columns along stylolite seams. Of the many workers who have investigated stylolites in the field none have recorded any structure associated with stylolite seams that could be construed, even remotely, as having been a collapsed column.

The analogy of fossil-capped stylolite columns to the "covering of pinnacles" is not an acceptable one, for the prominent feature of pinnacles is the circumferential erosion along the bedding planes and the lack of continuous vertical striations; on the other hand the prominent features of stylolite columns are a rather uniform thickness, the prominent vertical flutings and the complete absence of horizontal solution ridges such as are found along the solution surfaces of limestones due to the impure resistant layers. Similar horizontal resistant ridges should certainly be present on stylolite columns if they were formed by solution of moving water on the ocean floor approaching the columns from the sides as the theory demands, and why should the dissolution stop to form a cylindrical column?

Assuming that a column could be formed by solution as postulated and that the very soft column is capped with a hard shell, it is not understood by the writer how the column could become indurated and still maintain the cross-sectional area and the peripheral markings like that of the overlying shell.

In many stylolite seams there are numerous shells or fragments of shells within the columns and often the same species as those at the tops of the columns. Similar shells must have been scattered throughout the mass of the limestone which supposedly has been removed by solution according to Prokopovich's theory. Such shells should have been as insoluble as those forming the caps and consequently they should occur as a shell concentrate in the clay partings, yet no concentration of shells in the insoluble clay partings have been described that could have originated in this manner.

In examining the solution theory of Prokopovich and applying it to the natural occurrence of stylolites, the writer finds it entirely unacceptable and he is unable to find any phenomenon associated with stylolites that can be logically and satisfactorily explained thereby. It appears that the author of the theory had not given due consideration to the physical and chemical properties of the substances of which stylolites are composed and the environment in which he would have them develop.

REFERENCES

ALBERTI, F. V., 1858, Ueber die Entstehung der Stylolithen: Jahresh. d. Verein f. Vaterl. Naturk, in Württemberg, p. 292.

BONNYCASTLE, R. H., 1831, Continuation of the essay on the transition rocks of the Cataraqui: Am. Jour. Sci., v. 20, pp. 74–82.

EATON, AMOS, 1824, Report on the district adjoining the Erie Canal, Geology of New York, p. 134.

EMMONS, EBENEZER, 1842, Geology of New York, Part II, comprising the survey of the Second Geological District, p. 111.

FUCHS, THEODOR, 1894, Ueber die Natur und Entstehung der Stylolithen: Sitzungsber. d. k. Akad. d. Wiss. math.-nat. Kl. Wien, Bd. 103, pp. 673–688.

GÜMBEL, 1882, Ueber die Bildung der Stylolithen, etc.: Zeitschr. d. Deutsch. geol. Ges., p. 642.

———, 1888, Ueber die Natur und Entstehungsweise der Stylolithen: Zeitschr. d. Deutsch. geol. Ges., p. 187.

HALL, JAMES, 1843, Geology of New York, Part IV, Comprising the survey of the Fourth Geological District, pp. 95–96, 130–131.

HUNT, T. STERRY, 1863, Geological survey of Canada: report of progress from its commencement to 1863, pp. 631–634.

MARSH, O. C., 1867, On the origin of the so-called lignilites or epsomites: Am. Assoc. for Advance. of Sci. Proc., v. 16, pp. 135–143.

MEYER, H. v., 1862, Mitteilung: N. Jahrb. f. Mineral, etc., p. 590.
PLIENINGER, 1852, Ueber Stylolithen: Jahresh. d. Verein f. vaterl. Naturk in Württemberg, p. 78.
PROKOPOVICH, N., 1952, The origin of stylolites: Jour. Sedimentary Petrology, v. 22, pp. 212–220.
QUENSTEDT, A., 1837, Die Stylolithen sind anorganische Absonderungen: Wiegmann's Arch., pp. 137–142.
ROSSMÄSSLER and COTTA, 1845–46, Grundriss der Geognosie, p. 128.
SHAUB, B. M., 1937, The origin of cone-in-cone and its bearing on the origin of concretions and septaria: Am. Jour. Sci. v. 34, pp. 331–344.
———, 1939, The origin of stylolites: Jour. Sedimentary Petrology, v. 17, pp. 47–61.
STOCKDALE, PARIS B., 1922, Stylolites: Their nature and origin: Study No. 55, Indiana University Studies.
VANUXEM, LARDNER, 1838, Geology of New York, Second Ann. Rept., p. 271.
———, 1842, Geology of New York, Part III, Comprising the survey of the Third Geological District, pp. 107–109.
ZELGER, 1870, Ueber Stylolithen: N. Jahrb. f. Mineral. etc., p. 833.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 67–71
FIGS. 1–3, MARCH, 1955

CLASTIC CASTS OF HALITE CRYSTAL IMPRINTS FROM THE ROME FORMATION (CAMBRIAN) OF TENNESSEE

H. K. BROOKS
Curator, University of Cincinnati Museum, Cincinnati, Ohio

ABSTRACT

On the undersides of beds of fine-grained sandstone, casts of imprints of cubes which had been partially buried in the underlying argillaceous sediments and then dissolved before being filled and covered with sand were found in the Rome formation in Grainger County, Tennessee. Thin sections reveal that the sand filling the imprints is micro-crossbedded and of the same composition and texture as that of the covering beds. The halite crystals which left the imprints in the argillaceous sediments probably formed in small pools on mud flats. This evidence of evaporite deposition should not be taken as an indication of supersalinity of the Rome Sea, nor should it be taken as proof of an arid climate in the region. Casts of imprints of halite crystals can be used to determine the sequence of deposition of strata.

INTRODUCTION

Many authors (Safford, 1869; Keith, 1895; Currier, 1935; Resser, 1938; and Butts, 1940) have noted the occurrence of ripple marks and mud-cracked surfaces in the Rome formation of lower Cambrian age in the Valley and Ridge province of Tennessee and Virginia, and primary structures in the Rome formation in east Tennessee are described and discussed by Harvey and Maher (1948). Despite these and many other field studies of this formation, no salt crystal casts seem to have been noted previously.

A large number of exposures of the Rome formation have been carefully examined by the author in search of trails. Only in the road cut at the south end of War Ridge in Grainger County, Tennessee have well preserved trails been found and at no other outcrop have casts of halite crystal imprints been discovered. The proportionately greater amounts of thin-bedded siltstone and sandstone in this section have apparently favored the preservation of these primary structures. The primary structures in this section also have been spared the obliterating effects of internal deformation and low grade metamorphism which affected the Rome deposits to the east and south.

OCCURRENCE

The initial discovery of casts of imprints of halite crystals was on a slab of fine-grained sandstone in a fall rock accumulation at the base of the road cut at the south end of War Ridge on U. S. Highway 25 E about 300 feet west of the bridge over Indian Creek, Grainger County, Tennessee. The finding of this specimen led to a prolonged search, but the layer from which it came was not discovered. On the basis of lithology and the position in which it was found, it must have come from a zone of thin-bedded, fine-grained, pink sandstone and green shale which occurs near the middle of the exposed section. No specimens bearing casts of halite crystal imprints were found in place in this zone, but in a zone of thin-bedded, red mudrock about 15 feet higher in the section, a thin stratum of sandstone has casts of salt crystal imprints on its undersurface.

DESCRIPTION

The slab of fall rock bearing the casts (fig. 1) consists of irregularly bedded, fine-grained, pink and dark gray, laminated sandstone. The layer is about seven-eighths of an inch thick. Apparent lamination of the sand is due to thin

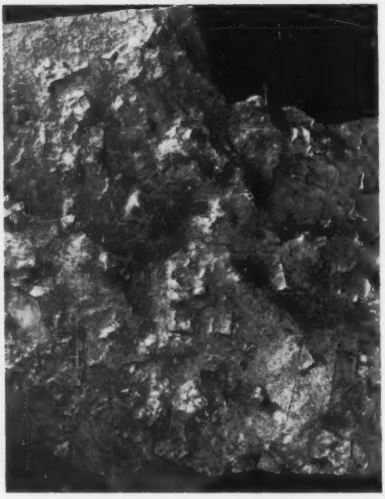


FIG. 1.—Part of the underside of the slab of sandstone from the Rome formation found in a fall rock accumulation. Casts of imprints of halite crystals are in relief (×½).

tongues and lenses of pink sand interfingering with impure, dark gray sand. In thin section, the dark layers seem to contain considerable carbonaceous material. On the side bearing the casts, a thin layer of olive-green, sericitic shale still adhers at many places.

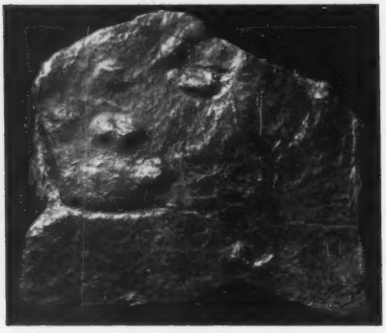


FIG. 2.—The underside of a piece of the thin layer of sandstone in the red beds with casts of halite crystal imprints. Note the mud cracks (×1).

The casts found in place (fig. 2) are on the underside of a thin layer, from one-eighth to three-eighths of an inch in thickness, of lensing, red, argillaceous sandstone which overlies a mud-cracked red mudrock. The upper surface of the sandstone layer is rippled.

The casts are of impressions of faces, corners and edges of randomly oriented cubes which were partially buried, 0.1 cm to 0.4 cm, in the muddy sediments. On the fall rock specimen, the casts indicate cubes from 0.3 cm to 1.0 cm on a side, with a mean size of 0.6 cm. The casts from the red beds are smaller, being about 0.2 cm to 0.5 cm on a side. The faces of most of the cubic crystals were not completely developed. Some of the casts on both of the figured specimens indicate the crystals were skeletal with hopper-shaped depressions on the sides of the cubes.

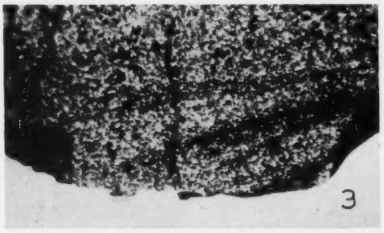


FIG. 3.—Photomicrograph of a thin section through a cast of a halite crystal imprint showing the micro-crossbedding of the sand filling the imprint. The material on both sides of the cast is sericitic shale which was originally the muddy sediment in which the imprint was made (×10).

Several thin sections through the casts were prepared from the piece of fall rock. The sections were cut perpendicular to the bedding plane in several directions. These sections revealed that the casts consist of fine, angular sand of the same texture as the laminated sandstone slab proper. Micro-crossbedding characterizes the sand casts of the crystal imprints (fig. 3).

ORIGIN

It is evident that the cubes which made the impressions had dissolved before fine sand drifted in over the sedimentary interfaces, filled the impressions and built up the layers of sandstone. This is proven by the structure and composition of the sand composing the casts.

Pyrite, galena, and halite are the only common minerals found in sedimentary rocks that crystallize in the cubic system. Crystals of pyrite, fluorite, and galena are always epigenetic and in contrast to halite they are relatively insoluble and chemically stable. Syngenetic cubic crystals of halite are not uncommon in sedimentary rocks. Thus, of these sedimentary minerals, only halite could form and dissolve in the sedimentary environment and during the time represented by the stratification planes on which the imprints were found.

During the growth of halite crystals, edges grow faster than crystal faces resulting in hopper-shaped depressions on the sides of the cubes. Later these depressions may be filled in to produce complete crystal faces. Therefore the evidence of skeletal crystals also is indicative of halite.

PREVIOUSLY REPORTED OCCURRENCES

Casts of halite crystal impressions and pseudomorphs have been reported from clastic and chemical deposits associated with evaporites of the Salina series, *i.e.*, Bertie waterlime and Camillus shale (Silurian), of New York (Ruedemann, 1925); from the Wellington formation (Permian) of Kansas (Dunbar, 1924); and from formations in which evaporites are otherwise unknown, such as the Kintla formation (Pre-Cambrian) of Canada (Daly, 1912), Rocke Miette formation (Cambrian) of Alberta, Canada (Kindle, 1929, and Raymond, 1930), Beekmantown limestone (Ordovician) of Pennsylvania (Miller, 1937), Newark series (Triassic) of the Appalachian region (Miller, 1937), and the Keuper formation (Triassic) of Germany (Trusheim, 1937). The above described structures are very similar to those mentioned by Kindle (1929) and Raymond (1930) and figured by Shrock (1948) from the upper Cambrian deposits at Roche Miette, Alberta, Canada. The lithology of the Roche Miette formation and the Rome formation is similar and both have an abundance of mud cracks and ripple marks on planes of stratification. Mud cracks and ripple marks seem to be commonly associated with casts of halite crystal imprints (Daly, Kindle, Raymond and Miller).

ENVIRONMENT

The presence of casts of halite crystal imprints should not be taken as proof of a supersaline Cambrian sea during the time of deposition of the Rome formation, nor should it be taken as evidence of general aridity.

The Rome formation is typically composed of variegated red, maroon, olive-green, and brown shales with a subordinate amount of sandstone, limestone, and dolomite. Carbonate rocks become more prominent to the southeast whereas sandstone and mudrock are more abundant to the northwest. Sandstones are especially common in the section exposed in War Ridge. The lithologic characteristics, ripple marks, and mud cracks have led most investigators to conclude that the Rome was deposited in shallow water. Vast mud flats which at times became subaerial undoubtedly existed as sediments were shed from a landmass to the northwest into the sedimentary basin. (Keith, 1895, and Harvey and Maher, 1948).

The casts occur in sediments which have every characteristic of mud flat deposits. Assuming that normal sea water originally filled a pool, after about nine-tenths of the water evaporated, halite crystals would begin to form on the bottom of the diminishing pool and would continue to grow until the pool dried up. There is about thirty times more sodium

chloride in sea water than calcium sulfate calculated per volume as anhydrite (King, 1947), the next most abundant salute; therefore, other evaporites would be precipitated only in minor amounts. The casts of halite crystal imprints on the mud-cracked surface in the red beds is suggestive of a pool that dried up completely.

In an area 10 cm by 10 cm on the slab of fall rock, 32 casts were measured. The total volume of the original crystals, if perfect cubes, would have been about 10 cm^3 or equivalent to 21.6 grams of halite per 100 sq. cm. The actual quantity of halite was probably considerably less since most of the cubes were incomplete. Even if .216 grams of halite was precipitated per sq. cm, a pool of normal sea water less than 8 cm deep would have contained enough sodium chloride. This depth was calculated on the assumption that the water in the Rome Sea had a salinity of 34.3 parts per 1000 and contained 27.21 grams of sodium chloride per kilogram as does Recent normal sea water (Kuenen, 1950). Precipitation in a pool in a depression on a mud flat would be from a brine concentrated from a pool of much greater original areal extent. These facts prove that the crystals could have formed in shallow pools on mud flats. The size of the crystals which made the imprints prove that supersaline evaporite pools existed for several weeks or even several months. In which case, it is probable that the pools were occasionally recharged by high tides.

Trilobites and brachiopods are common in some horizons of the Rome formation and excellent specimens of *Olenellus* have been collected in the lower part of the section exposed in the cut at War Ridge. The red mudrocks associated with the zones containing the casts of halite crystals contain trails and "nests" of the *Cruziana* type which are believed to be trails of trilobites. The meager paleontological evidence is thus indicative of normal salinity in the open Rome Sea.

No evaporites or evidence of supersalinity, other than the casts of halite crystal imprints, are known from the Rome formation. The fact that the halite crystals had dissolved before the next influx of clastic sediments suggests that the Rome Sea was not supersaturated with salt. If the freshening which caused the halite crystals to dissolve was due to an influx of rain water, sediments probably would have washed into the pool before the crystals could have dissolved; and instead of fine sand, one would expect the rain to wash mud from the exposed mud flat into the pool. Apparently the mud flats were slowly inundated by tranquil sea water, and no clastic sediments were deposited until the halite was dissolved by the water of the open Rome Sea.

The climatic implication of the casts is that for two intervals of time, in a small area, evaporation exceeded precipitation. This cannot be taken as proof of general aridity. The crystals could have been precipitated during a dry season.

USE IN DETERMINATION OF SEQUENCE IN STRATIFIED ROCKS

In a theoretical discussion of imprints and casts of crystals and their significance as criteria for determining the sequence of deposition of strata containing them, Shrock (1949) states that "If . . . the . . . crystals . . . disappear through solution, imprints of the original crystals remain and, if the sediment is sufficiently indurated to retain them, may be filled with mud or sand and thus preserved. Counterparts in the form of . . . pseudomorphs would be preserved on the underside of the covering bed and would be composed of the same material of that bed." He refers to previously reported occurrences, but field observations to support his conclusions were non-existant.

Both of the specimens here described have the casts in relief on the underside of layers of sandstone. One was found in place, and the correct orientation of the other was proven by micro-crossbedding of the sand composing the casts. These casts, therefore, fulfill the relations postulated by Shrock (1949).

ACKNOWLEDGMENT

Dr. Robert R. Shrock of The Massachusetts Institute of Technology read a preliminary copy of the manuscript and suggested several improvements in the presentation. The specimens are now in Dr. Shrock's collection of primary sedimentary structures at M.I.T.

REFERENCES

BUTTS, CHARLES, 1940, Geology of the Appalachian Valley in Virginia: Geologic text and illustrations: Virginia Geol. Survey Bull., v. 52, 568 pp.

CURRIER, L. W., 1935, Zinc and lead region of southwestern Virginia: Virginia Geol. Survey Bull., v. 43, 122 pp.

DALY, R. A., 1912, Geology of the North American Cordillera at the 49th Parallel: Geol. Survey of Canada, Dept. Mines Mem., v. 38, 857 pp.

DUNBAR, C. O., 1924, The geologic occurrence and the environments of insects: Am. Jour. Sci., 5th ser., v. 7, pp. 171–209.

HARVEY, E. J., and S. W. MAHER, 1948, Lithology and primary structural features of the Rome formation: Tennessee Acad. Sci. Jour., v. 23, pp. 283–290.

KEITH, ARTHUR, 1895, Description of the Knoxville sheet: Geologic Atlas of the United States, U.S. Geol. Survey, folio no. 16.

———, 1928, Structural symmetry in North America: Geol. Soc. America Bull., v. 39, pp. 321–385.

KINDLE, E. M., 1929, The successions of fossil faunas in the eastern part of Jasper Peak: Am. Jour. Sci., 5th ser., v. 18, pp. 177–192.

KING, R. H., 1947, Sedimentation in Permian Castile Sea: Am. Assoc. Petroleum Geologists Bull., v. 31, pp. 470–477.

KUENEN, P. H., 1950, Marine geology. John Wiley and Sons, Inc., New York, 568 pp.

MILLER, B. L., 1937, Casts of halite crystals in the Beekmantown limestone: Pennsylvania Acad. Sci. Proc., v. 11, pp. 55–57.

RAYMOND, P. E., 1930, The Paleozoic formations in Jasper Park, Alberta: Am. Jour. Sci., 5th ser., v. 20, pp. 289–311.

RESSER, C. E., 1938, Cambrian System (restricted) of the Southern Appalachians: Geol. Soc. America Sp. Paper 15, 140 pp.

RUEDEMANN, RUDOLPH, 1925, Some Silurian (Ontarian) faunas of New York: New York State Mus. Bull., v. 265, 134 pp.

SHROCK, R. R., 1948, Sequence in layered rocks. McGraw-Hill Book Co., New York, 507 pp.

SAFFORD, J. M., 1869, Geology of Tennessee: Nashville, 550 pp.

TRUSHEIM, F., 1937, Triopsiden (Crust. Phyll.) aus dem Keuper Frankens: Paleont. Zeitschr., Bd. 19, pp. 198–216.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 72–77
FIGS. 1–4, MARCH, 1955

AN OCCURRENCE OF GYPSUM IN SOUTHWEST TEXAS

P. H. MASSON
Humble Oil and Refining Company, Houston, Texas

ABSTRACT

Gypsum in the form of crystals and rosettes of selenite has been found in subsurface clays and sands of the Laguna Madre mudflats of southwest Texas. The habit of the crystals is unusual, and the dominant crystallographic forms are (I11) and (I02). The manner in which the crystals grow larger at depth and become lens-like in shape also is of interest. It is concluded that the gypsum precipitates from highly saline sea water which periodically moves in wind-blown sheets across the surface of the mudflats and sinks into the underlying sediments.

INTRODUCTION

Gypsum in an uncommon form has been revealed during the course of field work in the Laguna Madre mudflats in southwest Texas, and additional information concerning this interesting occurrence has been provided by dredging operations along the Gulf Coast intracoastal canal where it crosses the flats area. The area in which the gypsum was found is an expanse of algae-encrusted coastal mudflats approximately 15 miles in length and 10 miles in width. On most older maps this feature is outlined as part of Laguna Madre proper and appears as a prominent indentation in the coastline of east central Kenedy County midway between Corpus Christi and Brownsville; on new maps the mudflats are shown as part of the mainland (fig. 1).

Most of the gypsum is in the form of selenite, and one of the most interesting features of the occurrence is the habit of the crystals and the progressive changes in their size and form which take place at successively deeper levels in the sediments beneath the mudflats. It seems probable that the selenite is derived from highly saline sea water which periodically moves in thin sheets across the surface of the flats.

MODE OF OCCURRENCE

In the topmost two or three inches of the laminated and thinly bedded clays and algal material of the mudflats, gypsum is present as euhedral crystals less than 0.5 mm long. The wrinkled, leathery crust of algal fibers, clay, and fine calcite which covers most of the

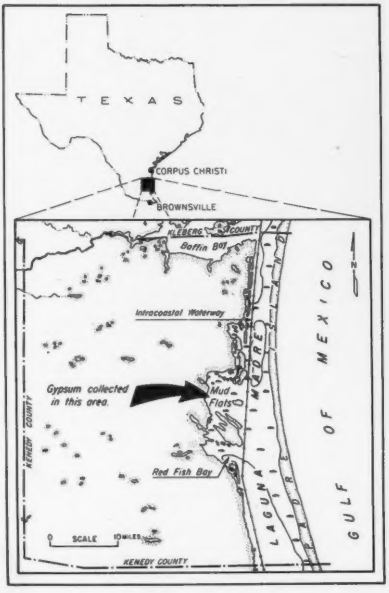


FIG. 1.—Location map showing Kenedy County, Texas, and the Laguna Madre mudflats. Gypsum was obtained in the area labelled Mud Flats and from spoil banks along the east side of the Intracoastal Waterway.

flats area contains euhedral selenite crystals, and in petrographic thin sections these can be seen scattered through the mass of dead algal fibers just below the surface layer of green living algae. Selenite is rare on the surface; euhedral crystals were found enmeshed in the topmost algal fibers, but most of the surface selenite was in the form of ragged windblown grains. In some areas, at depths of several feet, fine gypsum is abundant enough to form thin beds of gypsiferous clay and white layers of nearly pure gypsum; these gypsum layers in most places are less than one inch thick (fig. 2).

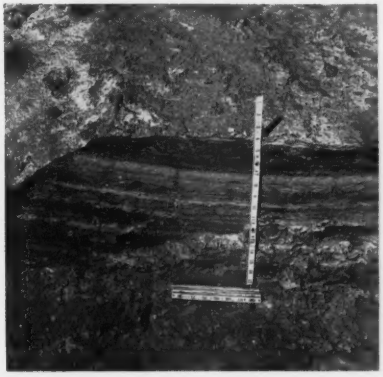


FIG. 2.—Interbedded layers of gypsum, clay, and algal material exposed in the wall of a trench. White layers are gypsum; wrinkled layers are buried algal crusts.

At depths below two or three feet the crystals are larger, and some have the form of rough, double-convex discs which bear no trace of rational crystal faces. Single and twinned crystals are present, but more common are delicate clusters of interpenetrating crystals between one and six inches in size. With increasing depth, more of the crystals have the lens-like form and fewer are euhedral or subhedral. Between the surface and depths of four or five feet all gradations from the euhedral form to the discoid form can be seen. The lens-like discoid individuals appear to have grown from euhedral crystals and may well be referred to also as crystals. At greater depths, however, large masses of compactly intergrown subindividuals are found; these aggregates more closely resemble the accretionary structures referred to as rosettes (Pettijohn, 1948). The rosettes and largest crystals were obtained from the sandy spoil bank along the intracoastal canal, having been brought up by suction-type dredges which excavated the canal to a depth of 15 feet. The largest rosette found was 20 inches in diameter (fig. 3).

FIG. 3.—Large selenite rosette dredged from a depth of approximately 15 feet in the Intracoastal Canal where it crosses the Laguna Madre mudflats. Rosette is dark gray in color due to very abundant included sand.

GENERAL CHARACTERISTICS OF THE CRYSTALS AND ROSETTES

Smaller crystals are perfectly euhedral, and all faces are fully and symetrically developed. The habit is that of a flat prism, diamond-shaped in cross-section and terminated by broad faces which cut the prism at a low angle. Unlike crystals with the habit most commonly recorded for gypsum, the Laguna Madre crystals are inclined to the *c* axis. The larger, rough-surfaced, lens-like crystals lie in a plane nearly normal to the *c* axis.

Aggregates of intergrown crystals are common and are composed of distinct crystals which interpenetrate in random manner. Rosettes, on the other hand, are made up of numerous discoid subindividuals closely intergrown in subparallel and radial arrangements. As accretion proceeds, aggregates of crystals apparently grow and become more complex until they assume the characteristics of rosettes. The subindividuals which are added during this later stage, however, appear to grow directly into the discoid form without starting as euhedral crystals. This difference in the manner of growth and mutual relations of the subindividuals is the basis for classifying these structures as rosettes rather than crystal aggregates.

All but the smallest crystals contain included quartz sand. The sand content varies in different crystals, and some have sand-free peripheral zones. In the larger crystals, aggregates, and rosettes, sand is very abundant and in most the selenite is little more than a cement. Crystals and rosette subindividuals, however, have crystallographic continuity so that they can properly be considered as sand crystals and sand rosettes similar to the so-called calcite sand crystals described and figured in some texts (Pettijohn, 1948).

Shells are included in some of the larger crystals, and sedimentary bedding is preserved as included sand layers of contrasting colors. The orientation of these beds is such that the discoid crystals must have grown with the planes of their maximum dimensions vertical or steeply inclined to the bedding.

OTHER SIMILAR OCCURRENCES OF GYPSUM

Gypsum similar to that of the Laguna Madre flats has been described from several other localities. A. Breithaupt (1841) described crystals from Bohemia and Silesia which were similar in habit to those of Laguna Madre. He commented on the discoid or lens-like shape which some of the crystals assumed, and stated further that they occur as nodules and clusters in the clays of tidal flats. C.A. Merritt (1935) described crystals from Alfalfa County, Oklahoma, with a habit somewhat like that of the Laguna Madre crystals; the environment here was a saline marsh. H. R. Bergquist (1942) figured, but did not describe in detail, single and twinned crystals in the Eocene Yazoo clay of Scott County, Mississippi. These crystals attained a maximum length of three inches and appeared to be most abundant along joints and bedding planes. In a recent account by Eardley and Stringham (1952) crystals similar in habit to those of Laguna Madre were reported from subsurface clays at the margin of Great Salt Lake in Utah.

CRYSTALLOGRAPHY

The basic crystal habit from which the rough, double convex crystals and complex intergrowths and aggregates of crystals develop consists of the unit pyramid, *l* ($\bar{1}11$), and broad, rough surfaces approximately parallel to *G* ($\bar{1}02$). The four faces of the monoclinic unit pyramid form a flattened prism; the ($\bar{1}02$) faces truncate this prism at a low angle so that the crystal has broad terminating faces (fig. 4a).

These forms are referred to the crystallographic setting for gypsum described by Palache, Berman, and Frondel (Dana, 1951), and it should be noted that the

orientation used here is different from that of other texts and reference books in current use.

It has been reported that faces of the form *e* ($\bar{1}03$) are usually rough and convex and that, together with ($\bar{1}11$), they sometimes form rounded, lenticular crystals (Dana, 1951). Angular relations in the Laguna Madre crystals, however, indicate that here the rough terminating surface is parallel to ($\bar{1}02$) rather than to ($\bar{1}03$). This surface does not have the appearance of a rational crystal face, but on smaller crystals it is a smooth plane the orientation of which can be measured with results that are reproducible within several degrees from crystal to crystal. Furthermore, the rough, lens-like crystals lie with their longest axes in a plane near ($\bar{1}02$) (fig. 4d).

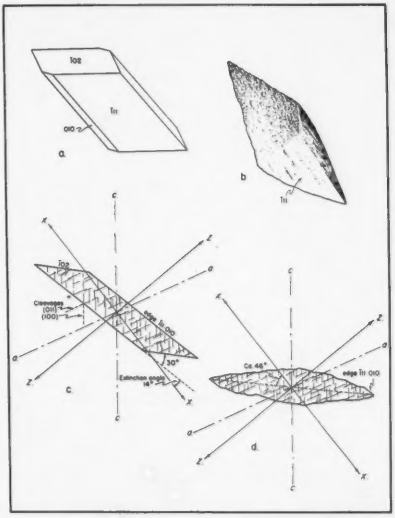


FIG. 4.—Habit and crystallographic orientation of selenite from Laguna Madre mudflats. a. Habit of euhedral crystals showing commonest form. Note that the crystal is viewed from the (−a, +b, +c) octant rather than the view customarily used in crystal drawings. b. Intermediate stage in the development of rough discoid crystals. The irregular surface approximately parallel to ($\bar{1}02$) has expanded so that ($\bar{1}11$) faces are partly obliterated and the crystal extends laterally in the direction of the *b* axis. c. Optical and crystallographic orientation of cleavage fragments from euhedral crystals. $\beta = 113°50\frac{1}{2}'$; $Z \wedge c = 51°52'$ (Dana, 1951). d. Optical and crystallographic orientation of cleavage fragments from discoid crystals.

The side pinacoid, *b* (010), which is prominent in crystals of the more common gypsum habit, is here restricted in its development to long, very narrow faces which truncate the acute edges between (111) faces. The unit prism, *m* (110), is present on some crystals as a very small face truncating the acute edge ($\bar{1}11$):($\bar{1}02$), but on most specimens this form is absent.

The crystals cleave readily on (010), and most of the crystallographic and orientation data were obtained on (010) cleavage fragments. Under the microscope, traces of weak cleavages on (011) and (100) can be seen. Treatment of (010) surfaces with dilute HCl accentuates the (100) cleavage traces and produces a rhomboidal etch figure bounded by the traces of (100) and (111). The extinction angle of (010) cleavage fragments is 14° measured from X to the sharply defined edges between ($\bar{1}11$) crystal faces and the (010) cleavage plane (fig. 4c). In most of the larger rough crystals described below, these ($\bar{1}11$) edges cannot be found, and the long axes of cleavage fragments are near the plane of ($\bar{1}02$); the angle between X and these axes of elongation appears to be about 46° (fig. 4d).

Twinning on the front pinacoid is fairly common; the resultant crystal has the shape of an obtuse V.

GROWTH OF CRYSTALS

The changes that take place as crystal enlargement proceeds are of considerable interest. As described earlier, the smallest crystals are terminated by ($\bar{1}02$); when sizes of one to two inches are attained, the ($\bar{1}02$) surfaces become irregular and convex and begin to grow at the expense

of ($\bar{1}11$) pyramid faces. The crystals extend laterally to points, and a diamond-shaped outline with the longest dimension parallel to the *b*-crystallographic axis is the result (fig. 4b). As the final discoid shape is approached, ($\bar{1}11$) becomes restricted to long, narrow faces fringing the edges of the rough, irregular, convex surfaces, and the outlines of the flattened plate becomes more nearly circular. With the disappearance of all rational crystal faces, a double-convex disc, the maximum dimensions of which lie in a plane approximating ($\bar{1}02$), is formed.

Single discs may have diameters as large as six inches, but most commonly the crystals form an aggregate of interpenetrating discs. The arrangement of discs within the aggregates appears to be random; several small aggregates were examined on the universal stage, and no rational twin relationship between subindividuals could be found.

ORIGIN OF THE GYPSUM

The Laguna Madre flats are two to three feet above sea level and extend across Laguna Madre dividing it into two bodies of water. Padre Island is about 110 miles long and, except for narrow passes at each extremity, isolates Laguna Madre from the Gulf of Mexico. Tidal fluctuations in Laguna Madre are small, but persistent winds from either the southeast or northeast periodically drive lagoonal waters onto the flats. During the summer months, the area frequently is covered by several inches of water. During dry periods the water table may drop as much as one and one-half feet below the surface. It is readily apparent that these thin sheets of windblown water, fed without recirculation from Laguna Madre, will become highly enriched in dissolved salts as a result of evaporation. The trend of this enrichment can be traced from a comparison of three water, analyses quoted in table 1. These analyses represent normal sea water, Laguna Madre water from Red Fish Bay at the northerly end of the south arm of the lagoon, and water from a shallow pond inland on the flats. No complete analysis of water from the moving windblown sheets on the flats surface is available, but the chloride content of one such sample was found to be 79,650 ppm.[1]

On a few occasions, extensive white crusts of precipitated salts including gypsum have been observed, and artificial pits in which water stands and evaporates become filled with coarsely crystalline halite. A small amount of fine gypsum with the crystal habit described above is disseminated through these salt deposits. Usually only minor amounts of salt are to be seen on the surface, and apparently the water recedes from the flats or filters downward through the clay and algal layers without precipitating appreciable amounts of solids. Withdrawal of water by evaporation at the surface during dry periods, however, may bring about precipitation of gypsum beneath the surface algal crust and in the clays near the surface.

Halite is present in the surface layers

TABLE 1.—*Major constituents in ppm of seawater and water from Laguna Madre and environs*

	Sea water[1]	Red Fish Bay[2]	Pond on flats[2]
Chloride	19,443	26,250	66,000
Sulfate	2,711	4,500	10,200
Carbonate	—	24	36
Bicarbonate	143[3]	148	74
Sodium	10,800	16,417	41,189
Calcium	411	671	827
Magnesium	1,303	1,084	2,942

[1] After Sverdrup, Johnson, and Fleming (1942, table 35).

[2] Analysis by Humble Oil & Refining Company Service Laboratory.

[3] All carbon expressed as bicarbonate.

[1] Analysis by M. S. Taggart, Jr., Humble Oil & Refining Company.

and in some places forms a matrix for fine-grained gypsum. The quantitity of halite in proportion to the amount of gypsum, however, is much less than should be expected from the proportions of ions equivalent to these two salts indicated in the water analyses quoted above. It must be assumed, therefore, that water in the sediments and on the surface remains for the most part undersaturated with respect to the more soluble salts; furthermore, there is sufficient fresh water from rainfall on the mudflats and adjacent areas inland to remove most of these salts from the sites of gypsum precipitation.

It is possible that growth of large crystals and rosettes at depth can be attributed to two factors: namely, change in the nature of the clastic sediments with depth, and the greater age of the deeper horizons. Sand beds are thicker and more abundant below the upper topmost few feet of laminated clays. High porosity and permeability in these beds as contrasted with the predominantly argillaceous beds would permit rapid ionic migration to a few large centers of crystallization and thus promote growth of large crystal aggregates and rosettes in the sand beds. The abundance of included sand in the more deeply buried gypsum indicates that it did indeed form in sediments composed almost entirely of sand. This gypsum may have been deposited originally at or near the surface as thin beds of fine crystals and subsequently become concentrated in the form of scattered large crystals and rosettes. Alternatively, it may have been derived entirely from external sources through the medium of moving subsurface brines. Either process would have been operative longer in the older, deeper beds and thus would account for the observed evidence of downward increase in size of the crystals and accretionary masses.

REFERENCES

BERGQUIST, H. R. and MCCUTCHEON, T. E., 1942, Scott County Geology: Miss. Geol. Surv. Bull. 47, 135 pp.

BREITHAUPT, A., 1841, Vollständiges Handbuch der Mineralogie: Band 2, Leipzig.

DANA, J. D., 1951, The System of Mineralogy. 7th ed., v. 2, by C. Palache, H. Berman, and C. Frondel; John Wiley and Sons Inc., New York, 1124 pp.

EARDLEY, A. J. and STRINGHAM, BRONSON, 1952, Selenite crystals in clays of the Great Salt Lake: Jour. Sedimentary Petrology, v. 22, pp. 234–338.

MERRITT, C. A., 1935, Gypsum Crystals from Alfalfa County, Oklahoma: Am. Mineralogist, v. 20, p. 674.

PETTIJOHN, F. J., 1949, Sedimentary Rocks. Harper and Brothers, New York, 526 pp.

SVERDRUP, H. V., JOHNSON, M. W., and FLEMING, R. H., 1942. The Oceans. Prentice Hall, New York, 1087 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 25, NO. 1, PP. 78–79
MARCH, 1955

DISCUSSION

SOME REMARKS ON CYCLIC CALCAREOUS SEDIMENTATION AS AN INDEX OF CLIMATIC VARIATIONS

ALBERT CAROZZI
Institute of Geology, University of Geneva

Recent studies in the Helvetic zone of the Swiss Alps have led W. Brückner (1951, 1953) to the conclusion that calcareous cycles are due chiefly to climatic variations. A critical examination of this hypothesis, partially given in other publications by the writer (1951, 1953, 1954) shows that it does not fit in with many petrographic features.

Following the climatic hypothesis, a close relation between the development of shaly or marly beds during cold periods (deep water) and of limestones during warm periods (shallow water) may be assumed. Accordingly diminution of depth must correspond to a lithologic sequence which leads from shaly beds at its base through alternating marl and limestone beds to a more or less massive limestone complex at the top. The reverse sequence is inconceivable and, moreover, shales are always relatively deep-water sediments and limestones shallow-water ones. Sedimentation conditions seem to have been oversimplified, since the existence of several types of shales and limestones as well as their possible different bathymetric positions have been entirely overlooked in spite of oceanographic evidences. Many helvetic cyles, for instance in the lower Cretaceous, during shallowing lead from pelagic limestones at their base through alternating limestones and marls to littoral shales at the top.

The main lithologic components of helvetic cycles reveal intergradations when traced laterally; in this way contemporaneity is easily demonstrated between cycles with different lithologic sequences. Thus, we may assume that without any appreciable depth differences limestones and shales have been deposited side by side. The climatic hypothesis seems unable to explain such facts which might easily be accounted for by the current pattern and by submarine topography of the epicontinental platform.

Moreover, within a given stratigraphic unit or length of time, the number of cycles varies from one point to another in the basin and not necessarily in relation to facies modifications. In order to explain such sedimentary behavior, important climatic fluctuations over short distances must be postulated, whereas the effects of contemporaneous tectonism of the framework accounts for it more satisfactorily.

We may add that deposits in given regions show a more or less uniform cyclic character through entire stratigraphic units as an expression of their tectonic control. These unstable zones evolve into definite tectonic units during the final period of diastrophism. The climatic hypothesis must claim, for these cases, close relations between submarine tectonic features and climatic fluctuations, which seem more than doubtful.

A subsidence of the helvetic trough during Cretaceous times is generally accepted, but that it kept pace with sedimentation is hardly conceivable. Such a conclusion may give rise to the view that the helvetic sedimentation is a very exceptional one, perhaps unique because it is entirely devoid of tectonic influences and especially of positive movements at least from the Upper Jurassic to the Eocene. Instead of this, clear evidence of disconformities as well as of unconfor-

mities appears as sharp breaks at the top of the major cycles (Purbeckian, Valanginian, Hauterivian, Albian, Senonian) recognized by P. Arbenz (1919). We may add that nearly all megacycles are closely related to tectonic phases. If these field observations are not overlooked, the climatic interpretation might lead to an intimate connection between the coldest periods and tectonic phases, a quite surprising conclusion for alpine geologists.

REFERENCES

ARBENZ, P., 1919, Probleme der Sedimentation und ihre Beziehungen zur Gebirgsbildung in den Alpen: Festschrift Albert Heim, Vierteljahrsschrift Natur. Gesell. Zürich, 64, pp. 246–275.

BRÜCKNER, W. D., 1951, Lithologische Studien und zyklische Sedimentation in der helvetischen Zone der Schweizeralpen: Geol. Rundschau, 39, pp. 196–212.

———, 1953, Cyclic calcareous sedimentation as an index of climatic variations in the past: Jour. Sedimentary Petrology, v. 23, pp. 235–237.

CAROZZI, A., 1951, Causes tectoniques et causes climatiques dans la sédimentation helvétique: Archives Sciences Genève, 4, pp. 439–442.

———, 1953, Données micrographiques sur le Crétacé supérieur helvétique: Bull. Institut Nat. Genève, 61, pp. 75–150.

———, 1954, Tektonik und zyklische Sedimentation in der Helvetischen Zone der Schweizer Alpen: Geol. Rundschau, 42, pp. 233–237.

Paleontology for the non-specialist

EVOLUTION of the VERTEBRATES

By EDWIN H. COLBERT

American Museum of Natural History

Written by one of the world's foremost paleontologists, this balanced, general account of vertebrate evolution is presented in terms that can be followed without previous knowledge of paleontology or anatomy. Avoiding advanced complexities and the slanting of specialist approaches, it stresses the fossil forms and places the various groups in their correct perspective from the viewpoint of geologic time. This simple but authoritative approach makes the work particularly useful as a survey and reference for readers in such allied fields as geology. The written material is amplified by detailed and effective drawings and diagrams. 1955. 479 pages. 157 illus. $8.95. Also available in a textbook edition.

Send today for an on-approval copy

JOHN WILEY & SONS, Inc.

440 Fourth Avenue **New York 16, N.Y.**

THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

P.O. Box 979, Tulsa 1, Oklahoma

Published Annual Volumes of the S.E.P.M. are Available at the Following Terms

JOURNAL OF PALEONTOLOGY*		Regular Price Per Vol.	Special to Members Per Vol.
Vol. 1 (1927)	Complete in 4 Nos., Reprinted 1948		
	Paper-bound copies	$ 6.00	$ —
	Cloth-bound copies	6.50	—
Vol. 2 (1928)	Complete in 4 Nos.	12.00	7.00
Vol. 3 (1929)	Only Nos. 1 and 2 Available	6.00	3.50
Vol. 4 (1930)	Only Supplement I Available	3.00	1.75
Vols. 5 to 8 (1931-34)	Each Complete in 4 Nos.	12.00	7.00
Vols. 9 to 11 (1935-37)	Each Complete in 8 Nos.	24.00	14.00
Vols. 12 to 19 (1938-45)	Each Complete in 6 Nos.	18.00	10.50
Vol. 20 (1946)	Only No. 6 Available	3.00	1.75
Vols. 21 & 22 (1947-48)	Each Complete in 6 Nos.	18.00	10.50
Vol. 24 (1950)	Only Nos. 2 to 6 Available	15.00	8.75
Vol. 25 (1951)	Only Nos. 2 to 6 Available	15.00	8.75
Vols. 26 to 28 (1952-54)	Each Complete in 6 Nos.	18.00	10.50
Vol. 29 (1955)	Non-Member, $15.00; Outside U.S. $15.40 Member, Covered by $8.00 dues, postpaid		
SINGLE ISSUES:	Non-Members, $3.00; Members, $1.75		

* Special discounts allowed to Non-Members on orders totalling $25 or more.

JOURNAL OF SEDIMENTARY PETROLOGY			
Vol. 1 (1931)	Only No. 2 Available	$ 2.00	$ 1.50
Vols. 2 to 4 (1932-34)	Each Complete in 3 Nos.	6.00	4.50
Vol. 5 (1935)	Only Nos. 1 and 2 Available	4.00	3.00
Vol. 6 (1936)	Only Nos. 2 and 3 Available	4.00	3.00
Vol. 18 (1948)	Only No. 3 Available	2.00	1.50
Vols. 20 to 23 (1950-53)	Each Complete in 4 Nos.	8.00	6.00
Vol. 24 (1954)	Only Nos. 2 and 4 Available	4.00	3.00
Vol. 25 (1955)	Non-Member, $6.00; Outside U.S., $6.40 Member, Covered by $5.00 dues, postpaid		
SINGLE ISSUES	Non-Members, $2.00; Members, $1.50		

SPECIAL PUBLICATIONS

Bibliography of Otoliths, by Robert B. Campbell, 32 pp. (Sept., 1929) .....$1.00 per copy

Turbidity Currents and the Transportation of Coarse Sediments to Deep Water, A Symposium, 107 pp. (Nov., 1951) ....Non-Members, $2.75; Members, $2.25 per copy

OIL MEANS SCIENTIFIC PROGRESS

Years of research . . . endless experiments . . . triumph after failure. And the magic of modern science gives us new uses every year for petroleum to make ours a better way of life. Schlumberger Services have played a major role in the oil development of the United States and Canada. They have materially reduced the cost of oil exploration, and have pointed the way to numerous discoveries.

. . . d Schlumberger means Service

Schlumberger Well Surveying Corp. • Houston, Texas

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

SOCIETY OFFICERS (APRIL 1954-MARCH 1955)

President: HANS E. THALMANN, Stanford, California

First Past-President: HAROLD N. FISK, Houston, Texas

Second Past-President: CLIFFORD C. CHURCH, San Francisco, California

Vice-President: FRANCIS J. PETTIJOHN, Baltimore, Maryland

Secretary-Treasurer: SAMUEL P. ELLISON, JR., Austin, Texas

Editor, Journal of Sedimentary Petrology: JACK L. HOUGH, Urbana, Illinois

Acting Editor, Journal of Sedimentary Petrology: RALPH E. GRIM, University of Illinois, Urbana, Illinois.

Editor, Journal of Paleontology: GROVER E. MURRAY, Louisiana State University, Baton Rouge, Louisiana

PACIFIC SECTION OFFICERS (1954-1955)

President: JOHN W. RUTH, Los Angeles, California

Secretary-Treasurer: WAYNE ELLIOTT, Long Beach, California

GULF COAST SECTION OFFICERS (1954-1955)

President: CHARLES W. STUCKEY, JR., Houston, Texas

Vice-President: E. H. RAINWATER, Jackson, Mississippi

Secretary: W. H. AKERS, New Orleans, Louisiana

Treasurer: FRED L. SMITH, JR., Houston, Texas

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

ASSOCIATION OFFICERS (APRIL 1954-MARCH 1955)

President: EDWARD A. KOESTER, Wichita, Kansas

Past-President: JOHN EMERY ADAMS, Midland, Texas

Vice-President: GRAHAM B. MOODY, San Francisco, California

Secretary-Treasurer: ELLIOTT H. POWERS, Fort Worth, Texas

Editor: ARMAND J. EARDLEY, Salt Lake City, Utah

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN